# TEXTILE FIBERS IN HIGH TEMPERATURE APPLICATIONS

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WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
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# FOREWORD

This report was prepared by staff members of the Materials Division and Textile Division, Mechanical Engineering Department, Massachusetts Institute of Technology under USAF Contract No. AF. 33(616)-5881. This contract was initiated under Project No. 7320, "Fibrous Materials for Decelerators and Structures", Task No. 73201, "Organic and Inorganic Fibers". The work was administered under the direction of the Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division, with Lt. B.R. Fox and Mr. J. Ross acting as project engineers.

This report presents the results of a literature survey conducted from July 1958 through July 1959.

# ABSTRACT
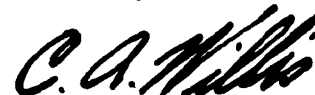
This project involved a survey of literature in the fields of metals, polymers and glasses to ascertain the availability of fibrous materials suitable for high temperature applications in re-entry parachutes.

Whereever possible, mechanical behavior of the material's fiber form was considered at the temperature level of 1500°F. But in many instances only bulk behavior of the material in question has been reported with an indication of its fabricating problems. It may be expected that continued work on such materials will, in a few years, enlarge the stable of fiber candidates for high temperature textile performance. Meanwhile there is at hand a small selection of stable, high temperature metal fibers capable of meeting the re-entry parachute requirements, although with some restrictions in weight, cost, and 'textile performance'.

## PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

C.A. WILLIS
Chief, Textiles Branch
Nonmetallic Materials Division
Materials Central

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# I. INTRODUCTION AND DESIGN CRITERIA

Under conditions of re-entry of space vehicles into the atmosphere of the earth or other planets very high stagnation temperatures may be encountered. The particular phase of the re-entry problem that is of interest here concerns the development of materials for high drag-to-mass ratio deceleration systems. It appears that a reasonable goal for operating temperature of such devices is about 1500°F in such deceleration systems. Conventional textile fibers used in parachute materials today are limited to applications below 400°F and it is unlikely that even experimental fibers comprised of organic high polymers can exceed a 500°F limit and maintain their desired mechanical properties.

The present report constitutes a critical literature survey and bibliography relating to the development of materials for high temperature drag devices. In principle three separate systems may be used in materials for such devices. The first would be a material which is heat resistant and suitably strong in its own right, either fiber or sheet material. Such materials may be metallic in nature and formable into continuous filament yarns which can be woven or formable into a sheet. The second principle would be the use of materials possessing required strength charac- teristics but which would, of necessity, be protected against chemical attack or oxidation by some type of inert coating. The third principle would be the use of fibers which are mechanically suitable at temperatures contemplated but which are limited to the staple fiber form. The last item would cause various difficulties in fabrication and achievement of maximum structural efficiencies.

Keeping in mind the foregoing principles of construction, the report is divided into several sections. One section considers the various types of metallic, non-metallic, and other materials, along with possible desirable surface treatments. Another section considers non-metallic materials. In addition, one section deals with considerations of fabrication, which will be very important regardless of whether present conventional parachute concepts (i.e. woven materials) are used or not. It is conceivable that for such high temperature, high velocity drag devices conventional parachute

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fabrication concepts will have to be abandoned altogether. It is possible that drag devices may be made out of assemblies of sheet materials. However, in order to limit the area of problems considered it has been assumed that none of the devices to be employed will be manufactured as structures possessing inherent rigidity over their total dimensions.

Basically the elevated temperature problem of drag devices is due to the heating effects of atmosphere which has reached its stagnation temperature at or near the surface of the drag device. The stagnation temperatures reached is a function of the square of the velocity or Mach number. Figure 1 shows the maximum temperature reached as a function of Mach number in sustained flight in the lower atmosphere. Figure 2 shows the maximum heating rate as a function of altitude and Mach number. Fortunately, drag devices are intended to be used over short times, so that maximum temperatures of steady state conditions may not be reached. While it is the purpose of this report to consider materials that may be useful in the temperature conditions up to 1500°F, it is beyond the scope of the work to make detailed design recommendations. It is obvious that the design of the fabric will affect its aerodynamic performance both as to stability and to heating. For example, if the parachute is made of a woven material it is entirely possible that shock waves could develop in the interstices between the fibers. This would result in enormous heating rates and destruction of the device. Conversely, by suitable design it may be possible to form the shock wave at a distance away from the forward surface, thereby minimizing the heat transfer to the drag device. There is, however, one important design consideration which is readily recognized. Due to the very low density of the atmosphere at high altitudes it seems evident that the porosity of the drag device will have to be extremely low, perhaps in the order of 1 per cent. It is this consideration that suggests that a non-conventional fabric and parachute design may be advisable.

The following mechanical properties appear to be of importance in materials for drag devices:

Short Time Tensile Strength   The short time tensile strength is the stress which can be withstood by the material in a test where time is not an important factor. In elevated temperature tests materials usually begin to deform as soon as load is applied, consequently the short time tensile strengths that are measured are approximate. However, they are useful in determining the maximum
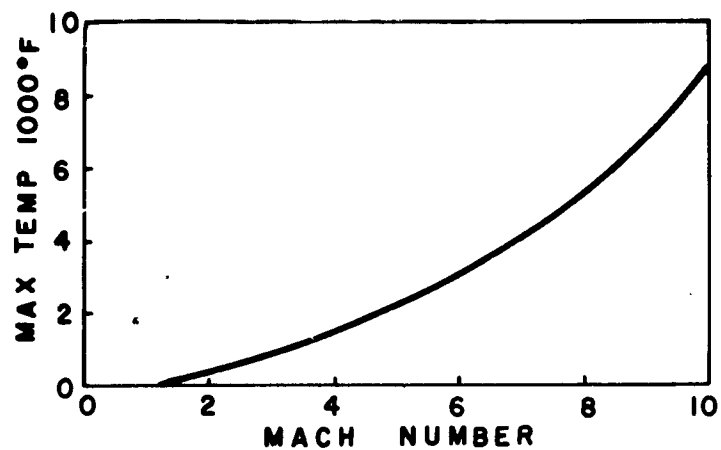
**Figure 1**    Maximum Temperature Attainable
in Sustained Flight in Lower
Atmosphere ( After Rowe, 12)
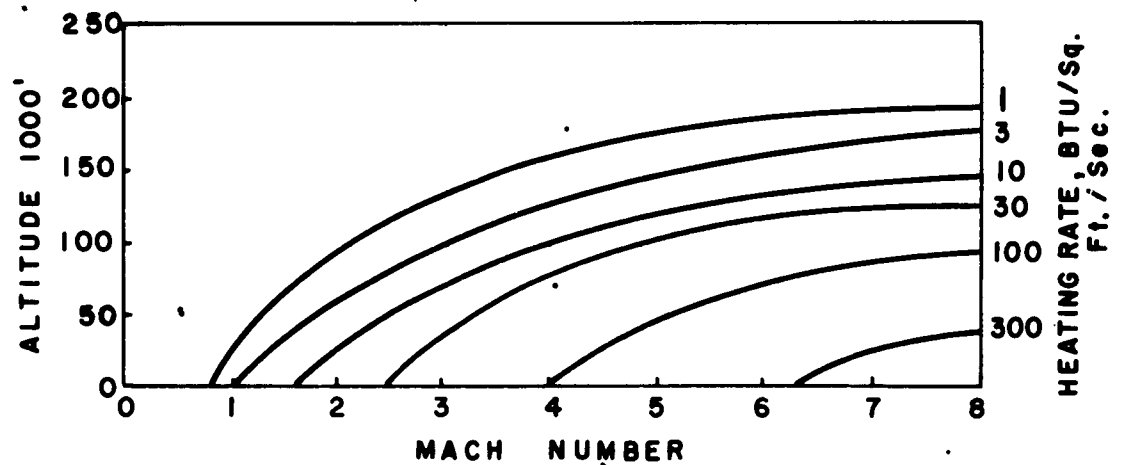


**Figure 2**    Maximum Heating Rate as a Function
of Altitude and Mach Number (After
Rowe, 12)

emergency loading which a fiber or other material could withstand.

Creep Strength   Creep is ordinarily defined as the deformation of a material under load with time. The short time creep characteristics of materials will be very important in the present application. Creep strength expresses the stress required for a fixed amount of deformation in a given time, it may also be expressed in terms of the stress required for a given rate of deformation. The latter definition in the present application does not seem particularly useful since the process will not be one of steady state. Relatively high creep strengths are desirable since excessive deformation will drastically alter the airflow characteristics of the retardation device.

Rupture Strength   Rupture strength is defined as the stress to failure in the creep process for a given life. If the geometry of the retardation device is such that deformation will not be very detrimental to the airflow characteristics then rupture strength becomes an important quantity. If the airflow characteristics are changed by excessive deformation then the rupture strength merely indicates the maximum level of stress that can be withstood before failure of the device will occur.

Ductility   Ductility in the terms of percent elongation in a given gage length expresses the amount of deformation that may be withstood by an individual fiber or member of the drag device before failure. Ductility may be measured in a short time tensile test or in creep or rupture tests. It is well known for metals that the higher the strain rate at elevated temperature the greater will be the resulting ductility. This is because the process at high metal extension rates is largely that of plastic flow, whereas the metal deformation that occurs at low strain rates is more akin to the viscous process with a resulting decrease in total elongation. Deformation at high temperature is important as indicated above. It might be noted here that some expansion of the structure will occur due to the normal expansion characteristics of the material with temperature. These will probably be much less important than the plastic extension due to plastic flow at elevated temperatures.

Elastic Constants   The elastic constants of Young's modulus and shear modulus decreased markedly with temperature. In rigid devices such as airframes this is an important consideration since the lowering of the elastic modulus is responsible for flutter. In a drag device operating at elevated temperatures,

however, most deformations will be of a plastic or permanent nature, and the permanent deformations will be many times those possible in the elastic mode. As a consequence the elastic constants may be of secondary importance in the present application.

Strength Weight Ratio. The strength weight ratio is of the utmost importance in any airborne or space device. Naturally this is a function of temperature, falling markedly as temperature increases. Consideration to this quantity will be given in the present survey.

Repeated Loaoing Characteristics. In a service application the drag device will be loaded monotonically presumably with the load rising to a maximum along with the temperature and then falling off. Repeated loading characteristics in the present application therefore include the problem of reuse of the drag device. Essentially the properties of interest here then are the strengths, residual strengths and ductilities inherent in a structure after previous usage at elevated temperature. Such properties are not ordinarily found in the literature, and in the case of particular materials of interest it will have to be investigated.

A second class of properties of interest in the present application may be termed general physical properties. The ones of interest are as follows:

Specific Heat Capacity. Naturally the higher the specific heat capacity the lower will be the temperature rise in a given application.

Thermal Conductivity. The greater the thermal conductivity, the higher will be the rate of temperature rise in the stress bearing member. A low thermal conductivity is therefore desirable.

Specific Volume or Density. Density has been considered above in the strength weight ratio. From the mechanical point of view a low density is desirable. From the thermal point of view, however, a high density or specific gravity may be a desirable characteristic.

Thermal Diffusivity. Thermal diffusivity is defined as the conductivity divided by the specific heat and specific gravity.

This ratio indicates the relative importance of the three specified physical properties above. For a low temperature rise the thermal diffusivity should be low. Figure 3 demonstrates the importance of thermal diffusivity in high temperature applications. The figure assumes two materials A and B with the same melting point and the same extent of temperature range where the metal has become semi-solid. However, the metals have different thermal conductivities. Because of the steep thermal gradient in material A only a small surface layer will be in the semisolid state and thus potentially removed. In material B, whose thermal capacity and diffusivity is much superior to metal A, half of the wall thickness will be in the semisolid state because of the high termal conductivity.

Emissivity and Reflectivity. The properties of emissivity and reflectivity are of importance where a structure is receiving heat from a radiant source, and where equilibrium conditions may prevail. It does not appear that these will be important properties in the present application.

The third class of properties of importance may be termed surface and chemical properties, they include:

•Frictional Characteristics. Frictional characteristics will be of importance in the fabrication of structures made from fibers. They will affect processes of weaving, knitting, etc. In addition the frictional characteristics of fiberlike materials will affect the ease with which the device may be deployed to assume its operational shape.

Surface Absorptivity and Chemical Reactivity. Absorptivity and reactivity are interrelated properties of extreme importance. The chemical reactivity will determine whether or not destructive corrosive action will occur at the surface (i.e. oxidation of the refractory metals), or stable chemical compounds of a protective nature can be formed (the oxidation of aluminum alloys). The kinetics of such reactions may be in part determined by the absorptive characteristics of the surface.

Ablation. Ablation is a description of a rather complicated series of reactions which properly include erosion, corrosion, evaporation, sublimation and other auxiliary processes, such as cracking or spalling due to thermal shock. Few if any ablation measurements have been carried out on materials which would be likely for retardation devices.
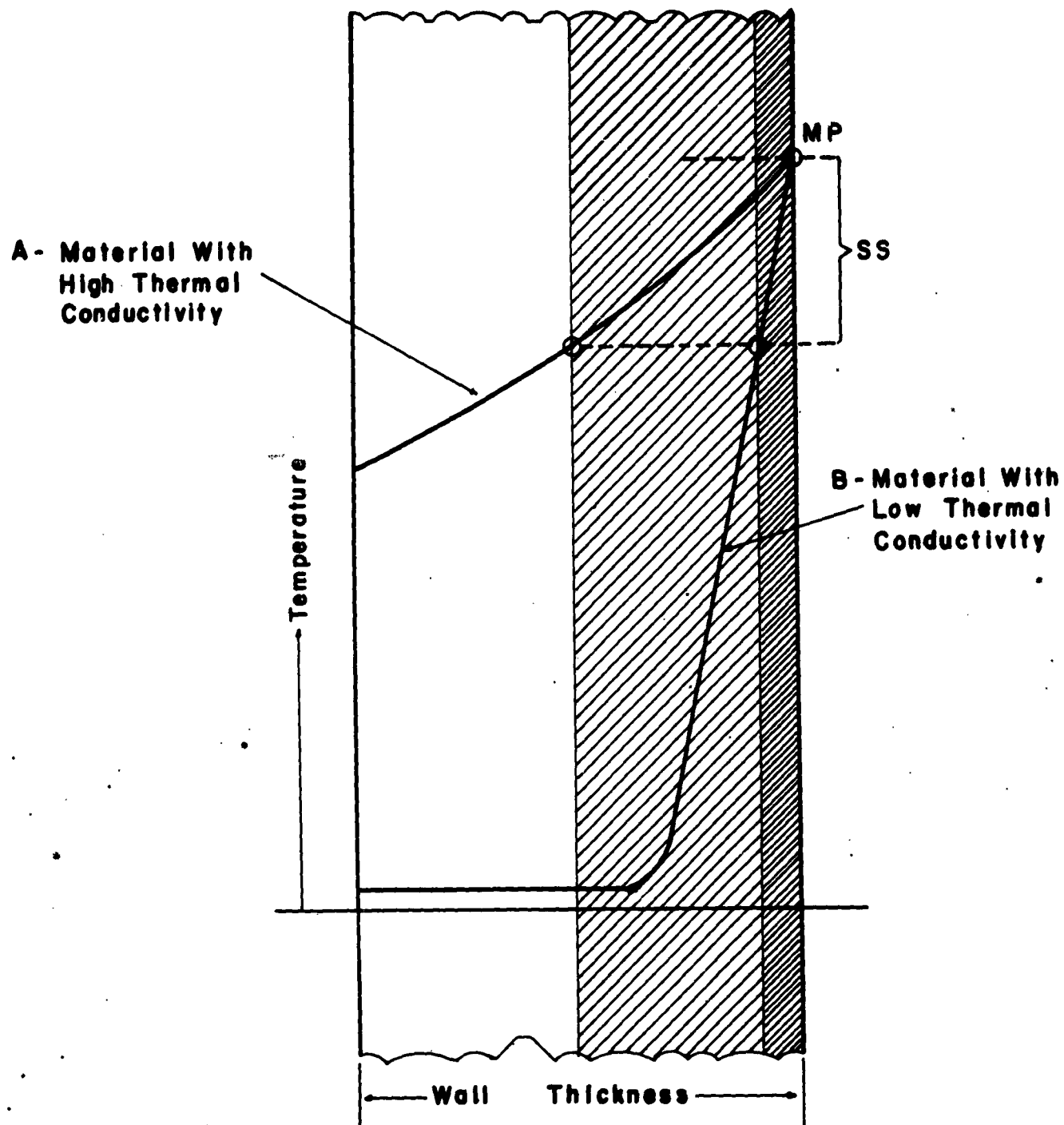
Figure 3   Effect of Semisolid Condition on
Performance (After Rowe, 12).

The final class of properties of importance is related to fabrication characteristics. Fabrication characteristics fall into two types, the first type concerns fabrication of the basic materials such as fiber or sheet from which a parachute can be formed. The second type of fabrication characteristic is concerned with the forming of the sheet or fiber into a drag configuration. In the case of fiber this means weaving into cloth and sewing into a chute. While characteristics concerned with wear and durability (e.g. increasing) do not strictly fall under the heading of fabrication they will be considered in this class.

From the foregoing listing of properties and characteristics of importance it is evident that a compromise must be made in choice of raw material. Those materials which are strongest may have such a high density that the strength weight ratio is low. Further, those with the highest strength weight ratio may have unfortunate chemical characteristics, such as being regularly oxidized. Finally, those that possess all other desirable characteristics may not be readily fabricated into a form that would be suitable for application.

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## II.  MATERIALS AND THEIR PROPERTIES

### A.  METALS

#### 1.  Refractory Metals.

The refractory metals are usually understood to include tungsten, rhenium, tantalum, molybdenum, and columbium.  Vanadium and chromium are also sometimes considered to be refractory metals. Both of these metals, however, in their pure form are in the early stage of current development.  It is probable that neither vanadium nor chromium will become practicable engineering metals for several years, and thus, will not be further considered.

Research on all of the remaining refractory metals has been given a great deal of emphasis in recent years because of the desire to use these metals and/or their alloys in the coated condition for jet engine blading, and in uncoated condition for rocket or nuclear applications.  Tungsten has a long technological history in the lamp and electronic industry and a great deal of information exists concerning it.  Next to tungsten, molybdenum is the metal which has received the most attention until recent years.  However, the remaining refractory metals tantalum, columbium and rhenium are more workable than either tungsten or molybdenum and rhenium is even stronger than tungsten.  A recent review of refractory metals was made by J.W. Pugh (1).

All of the refractory metals may be hot melted, sintered or hot worked, but special care is needed to prevent interstitial impurities such as carbon, oxygen or nitrogen from diffusing into them as they severely affect not only the physical properties but the workability.  Both molybdenum and tungsten possess high brittle-to-ductile transition temperatures and care must be taken to maintain the fabrication temperature above the transition temperature or else fracture will result.  In the case of both molybdenum and tungsten, recrystallization of worked structures causes a marked decrease in ductility because of the accumulation of impurities in the grain boundaries during the recrystallization process.

Table 1 summarizes  the properties of refractory metals under consideration.  Tungsten is the metal with the highest melting point, followed by rhenium, tantalum, molybdenum and columbium, the latter having a melting point of 2415°C, (4379°F) well above

## Table 1

### Properties of Refractory Metals

| Property | S | Re | Ta | Mo | Cb |
|---|---|---|---|---|---|
| Melting Point, $^{\circ}C$ | 3410 (8) | 3180 (7) | 2996 (8) | 2625 (8) | 2415 (8) |
| Density, g per cu cm | 19.3 (8) | 21.0 (7) | 16.6 (8) | 10.2 (8) | 8.57 (8) |
| Young's Modulus, $10^{6}$ psi | 51 (3) | 67 (7) | 27 (8) | 47 (5) | 15.1 (6) |
| Structure | BCC | HCP | BCC | BCC | BCC |
| Recrystn.Temp.,$^{\circ}C$(1hr) | 1565 (7) | 1400 (7) | 1275 (14) | 1130 (15) | 1050 (8) |
| Linear Therm.Exp.,coeff $10^{-6}$ per $^{\circ}C$ | 4.5 (3) | 6.7 (7) | 5.9 (16) | 5.6 (17) | 7.1 (8) |
| Therm.Cond.,cal per cu cm,$^{\circ}C$,sec. | 0.48 (8) | 0.17 (7) | 0.13 (8) | 0.35 (8) | 0.125 (18) |
| Vapor Pressure, at 2225°C | $1.38 \times 10^{-4}$ (19) | $1.18 \times 10^{-3}$ (7) | $7.94 \times 10^{-4}$ (19) | 0.50 (19) | $1.66 \times 10^{-2}$ (19) |
| Cost for powder,$ per lb. | 4.75 | 680.00 | 43.00 | 3.40 | 100.00 |

(1) Note: Numbers appearing in parentheses are reference numbers
(After Pugh, Ref.1)

the present range of consideration. Note that all of these metals
with the exception of tantalum and columbium have elastic moduli
much higher than that of steel. All are of the body-centered-
cubic structure with the exception of rhenium which is hexagonal-
close-packed. The recrystallization temperature listed in Table 1

is approximate, since this temperature depends both upon purity, amount of prior deformation and temperature at which deformation occurred. The cost figures in the table, given by Pugh, are approximate but it will be noted that rhenium is extremely expensive. This is due to its rarity in nature. The cost of columbium will probably decrease as its technology and use are better developed.

Pugh (1) has classified the mechanical properties of the body centered cubic refractory metals according to their positions in the periodic table. The group V-a metals, tantalum and columbium have a relatively high solubility for interstitials and a high degree of ductility. They are very susceptible to strain aging. Group VI-a metals, tungsten and molybdenum have a low solubility for interstitials. They have a ductile to brittle transition temperature which is very sensitive to the structure and are less affected by strain aging (1). Figure 4 shows tensile parameters for the group V-a metal tantalum (2). The strain hardening parameter m is defined here as the slope of the logarithmic stress-strain curves as given in equation (1), and is known as the strain hardening exponent, $\sigma$ is the flow stress or true stress, $\varepsilon$ is the strain and T is the absolute temperature.

$$m = \frac{\partial \log \sigma}{\partial \log \varepsilon}\bigg|_{\dot{\varepsilon},T} \tag{1}$$

Similarly, equation (2) defines the strain rate sensitivity, $\sigma_1$ in this equation is the flow stress at a particular testing rate, $\sigma_2$ the flow stress at some faster rate, $\dot{\varepsilon}_1$ is the faster rate and $\dot{\varepsilon}_2$ is the slower rate. This expression is evaluated for a particular strain.

$$n = \frac{\log \frac{\sigma_1}{\sigma_2}}{\log \frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}}\bigg|_{\varepsilon,T} \tag{2}$$

Figure 4 shows several interesting features for tantalum. At the lower temperature ranges the strength falls off very sharply with temperature. There are minima in strain rate sensitivity and elongation and maxima in strain hardening and strength curves. These features are indicative of strain aging. Since columbium and vanadium also belong to group V-a, they would be expected to behave in similar fashion. This has been corroborated by Pugh (3).

Figure 5. Effect of Deformation on Hardness, Ultimate Tensile Strength and Elongation of Tantalum.



Figure 4. Tensile Parameters for Tantalum, Typical of Group V-a Metals-as a Function of Temperature.

Figure 5 shows the effect of cold working on the hardness ultimate strength and elongation for tantalum. Figure 6 illustrates the tensile properties of tungsten, a Group VI-a metal (4). The maxima and minima in these properties indicative of strain aging are not particularly prominent. Below 500°K (227°F) the ductility is practically nil and tungsten may be considered a brittle metal in this range. This is a relative statement, of course, since both microstructure and test conditions will effect the ductility. Chromium and molybdenum (5 & 6) can be expected to behave in similar fashion. Figure 7 from the work of Pugh, shows tensile properties of molybdenum as a function of temperature.

Figure 8 shows the tensile strengths of the refractory metals plus one data point for chromium. Rhenium (7) is much stronger over the entire temperature range. This has been attributed to a high capacity for strain hardening (1 & 7). As before noted this is the only one of the refractory metals which is hexagonal close packed. The dotted curves in Figure 8 indicate uncertainty of data (1 & 8). Figure 7 (after Pugh) shows that for the group VI-a metals, there is a distinct relationship between melting point and strength level. Here the tensile strength has been plotted versus the homologous temperature where homologous temperature is defined as the ratio of the absolute testing temperature to the absolute melting temperature.

Figure 9 is a plot of rupture strength as a function of temperature for ten hour life for four of the metals. No data was available in the literature for tantalum. It is noted that at very high temperatures the ten hour rupture strength of tungsten approaches that of rhenium. Molybdenum and columbium are somewhat weaker. Pugh (1) has compared stress rupture properties by means of the Larsen-Miller parameter (9) and on the basis of this believes that rhenium is most outstanding for lower temperatures and shorter times. While the Larsen-Miller parameter is by no means exact, it is an excellent guide.

The principal controlling property of the refractory metals at elevated temperatures is their extreme susceptibility to oxidation. It is this susceptibility that has prevented the utilization of their excellent strength characteristics. Figure 10 is a plot of the relative oxidation attack for one hour exposures of the refractory metals as a function of temperature. It will be noted that rhenium and molybdenum have the poorest oxidation characteristics while tungsten has the best. In regard to the latter, it
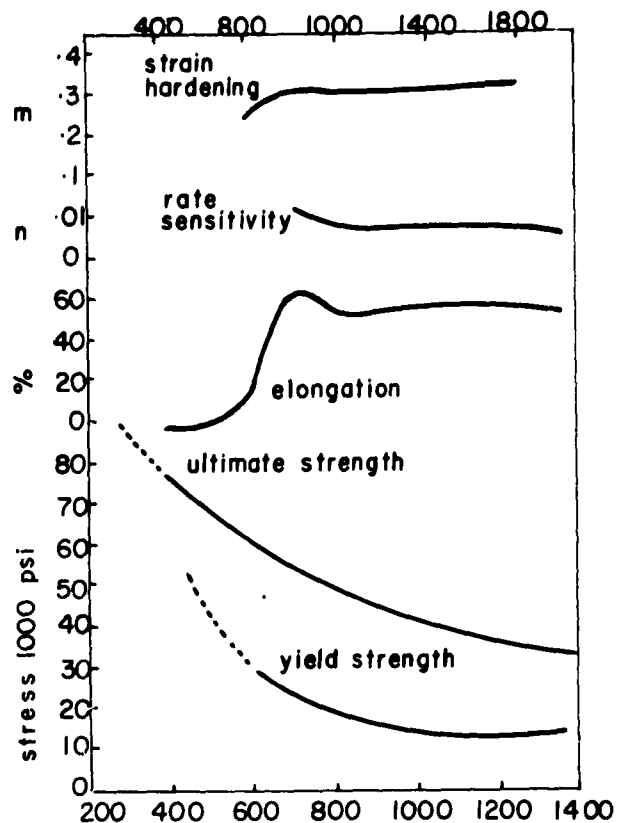
Figure 6    Tensile Parameters for Tungsten -
Typical of Group VIa Metals as
Function of Temperature °K
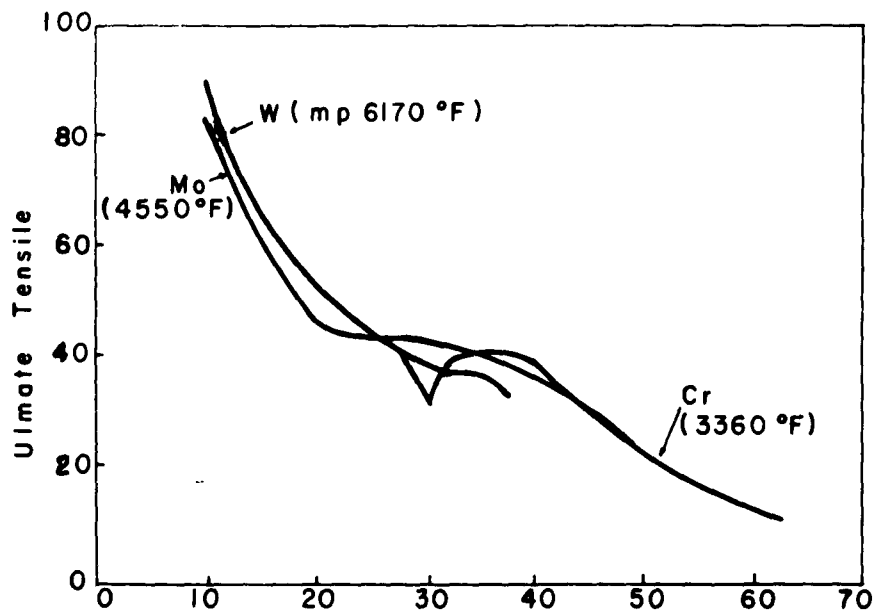


Figure 7    Strength of Refractory Metals as a Function
of Homologous Temperature, or Test Temperature
in % of the Absolute Melting Point

Figure 9  Rupture Strength as a Function of Temperature for 10 Hrs. Life.



Figure 8  Tensile Strength of Refractory Metals as a Function of Temperature.
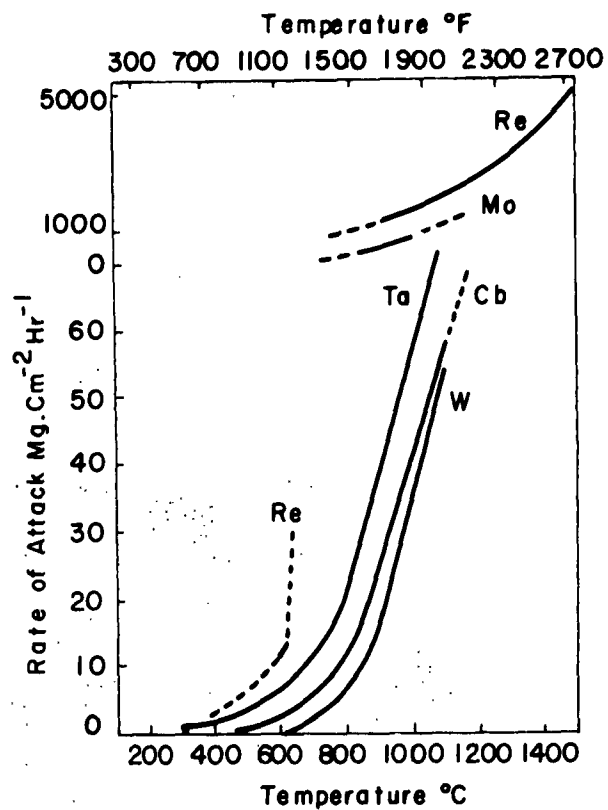
Figure 10   Relative Oxidation Attack
for 1 Hour Exposures as a
Function of Temperature.
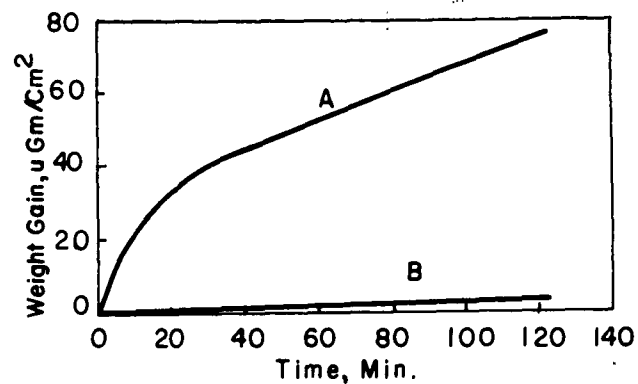


Figure 11   Effect of Oxygen and of
Nitrogen on Columbium at
Elevated Temperatures. Curve
A is for Oxygen at 375°C;
Curve B is for Nitrogen at
400°C.   Pressure of Gas was
76 mm Hg Each Test.

might be noted that the best is none too good at any temperature of practical interest.

None of the refractory metals form tight oxide scales that prevent further reaction. Many of the refractory metal oxides are extremely volatile or have very low melting points. Rhenium for instance, oxidizes catastrophically above 600°C (1112°F) forming $Re_2O_7$. This compound melts at 289°C (534°F) and boils at 363°C (686°F) (1).

Oxidation of columbium in air becomes serious at roughly 400°C (10). At this temperature and above $Cb_2O_5$ is formed. The melting point of the oxide is 1440°C (2624°F) with little vaporization of the oxide below 1370°C (2498°F). However, oxygen has a high diffusion rate in columbium and rapidly increases its hardness. See Fig. 11, 12. Tantalum is similar in its behavior. See Figure 13 and Figure 14.

The oxidation of tungsten only becomes serious above 600°C (1112°F) (11). The scale growth is determined by two processes, namely the diffusion of oxygen and the volatility of the scale. Up to 1350°C (2462°F) which is perhaps beyond our range of interest, the oxygen diffusion is controlling.

While much work has been done on coatings for refractory metals, particularly molybdenum, none of the coating techniques have really been successful for the turbine blade applications for which they were intended. Some of the molybdenum coating techniques have been extended to tungsten (12). A great difficulty with coatings is that they break in the presence of mechanical abrasion and allow oxygen to enter. In the present case where thin sheet or wire is contemplated, the ratio of surface area to volume is extremely high and even minor breaks in coatings could not be tolerated.

There has been some success in the development of oxidation resistant columbium alloys by additions of titanium and other metals (13). However, the resulting columbium alloy is comparatively brittle and not amenable to fabrication.

In conclusion, for the temperature range at hand up to 1500°F, the refractory metals do not seem to have much to recommend them. It is true that up to this temperature, which is equivalent to 815°C, rhenium possesses remarkable strength. Its extreme cost,
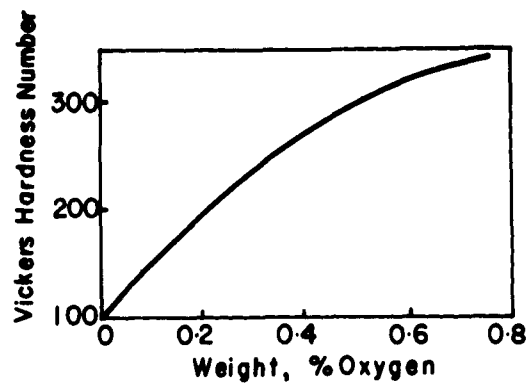
Figure 12   Effect of Oxygen on Hardness of
Columbium.
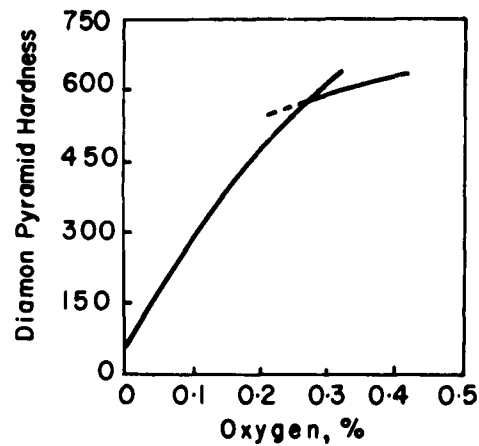


Figure 13   Effect of Oxygen on Hardness of
Tantalum.   Samples in Curve A
were disclosed;   Samples in
Curve B remained bright.
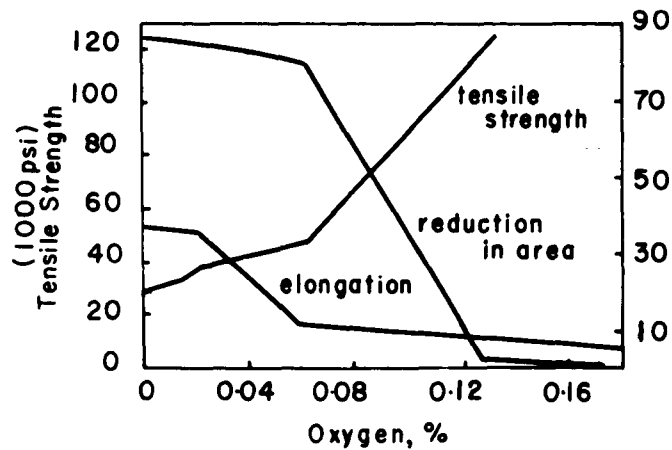


Figure 14   Effect of Oxygen on Tensile
Properties of Tantalum.

however, eliminates it, as does it rarity. The principal reason
for eliminating the refractory metals entirely, however, is their
susceptibility to oxidation. Insofar as the strengths of the
remaining refractory metals is concerned, as will be later seen
on a strength-weight basis, the refractory metals present no
advantage over much more common and more readily available materials.

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# A. METALS (Continued)

## 2. Light Metals

Most of the common structural materials can be used at elevated temperatures. Aluminum alloys, magnesium alloys, alloy steels, titanium alloys, stainless steels, and the high temperature alloys, all have somewhat distinct areas of usage. Aluminum alloys and magnesium alloys are eliminated from the present discussion because of their service temperatures are too low. Pure magnesium melts below 1200°F, and pure aluminum just above this temperature. Their poor mechanical properties are shown in Figure 15. Table 2 shows the general temperature range of usage for each class of materials. The low and high temperature cited for each material are indicative of the range only and are not absolute limits for the materials. The limiting service temperature for a given alloy is a strict function of the particular design it is to be used in. For comparison, metals other than light metals are also listed.

## Table 2

### General Temperature Range of Usage

| Alloy Family | Useful Temperature Range |
|---|---|
| Aluminum alloys | Rt to 500°F |
| Magnesium alloys | 400°F to 800°F |
| Alloy steels | Rt to 1200°F |
| Titanium alloys | 500°F to 1100°F |
| Stainless alloys | Rt to 2200°F (for oxidation resistance) |
| Age Hardenable S.S. | Rt to 1000°F |
| High temperature alloys | 1000°F to 2100°F |
| Molybdenum alloys | 1600°F to 2500°F |
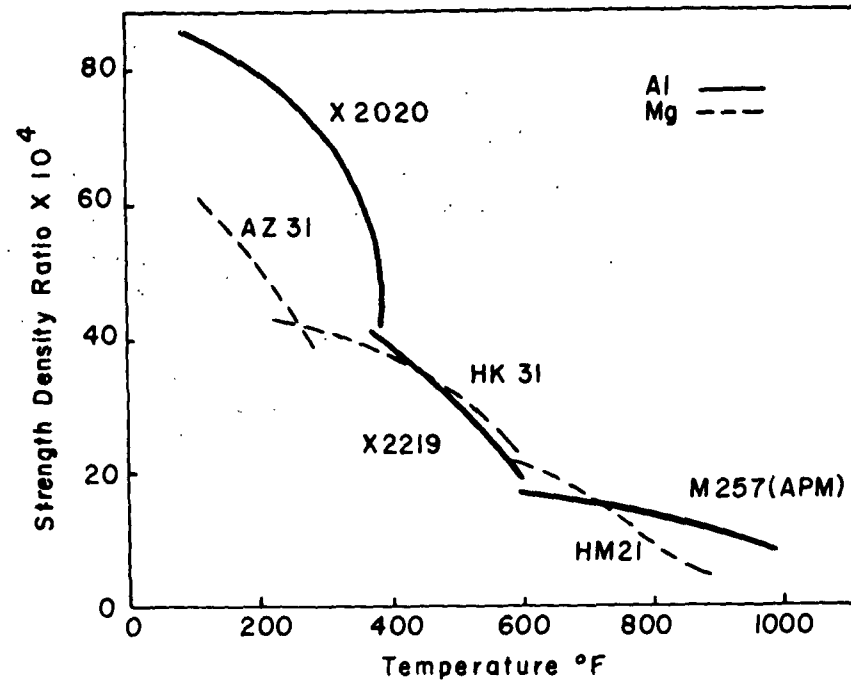
Figure 15    Capabilities of Today's Best Aluminum
             and Magnesium Alloys for Elevated
             Temperature Applications.  Strength-
             Density Ratio is Ultimate Strength in
             psi to Density in lb/cu. in.

It should be emphasized at this point that the yield strength/ weight ratio is only one criteria in the selection of a material for its strength properties. For applications where inherent stiffness is needed in the structure, the density of the metal and the variations of elastic modulus with temperature can play a more important part in the final selection of the material than the tensile strength.

In the following sections, data on various outstanding light metals are presented that will allow the fabricator or designer to choose intelligently the proper metal for a specific end use.

## Titanium

Its strength-to-density ratio is titanium's most publicized property. In this respect it is superior to many metals over an intermediate although wide temperature range. Figure 16 gives a comparison of yield strength density ratio as a function of temperature for titanium, beryllium and alloys. On this basis the hot worked die steels are the most competitive materials if only properties (and not cost or fabrication difficulties) are considered. Beryllium with its low density will be competitive when it becomes more available. The top curve in Figure 15 represents the new all beta titanium alloys providing cost, fabrication and health problems are overcome. It has the potential of being heat treated to over 250,000 psi ultimate tensile strength. In the laboratory the alloy has been heat treated and cold worked to a tensile strength of over 270,000 psi. The maximum future possible temperature for use of titanium appears to be about 2000°F for a very short time exposure, and 1100°F for a long time property. Creep strength is not necessarily the limiting factor at high temperatures. Above 1100°F titanium absorbs oxygen and nitrogen at rates sufficient to interfere with its usefulness. Some producers consider 1000°F the upper limit for continuous service, and 1500°F for short time. Isochronous creep curves such as shown in Figure 17 for Ti-5, Al-2.5, Sn, are used by designers in working with short and long time creep data. For example, if a part were designed for an aircraft structure using Ti-5, Al-2.5, Sn, you should have an allowable total deformation of 0.6% for 1000 hours at an operating temperature of 900°F. the limiting stress would be about 18,000 psi. However, if the material were to be used for a missile structure it could be used at a stress level of about 50,000 psi for one hour of exposure. Since titanium can withstand such high stress levels for short periods of time it is an excellent metal for missile application.

## Figure 16

All-Beta Titanium
Alloy Compared
with Beryllium
and Ferrous-Base
Materials on a
Strength-to-
Density Basis at
Elevated Tem-
peratures. Strength-
Density Ratio is
Yield Strength in
1000 psi. to
density in lb. per
cu. in.
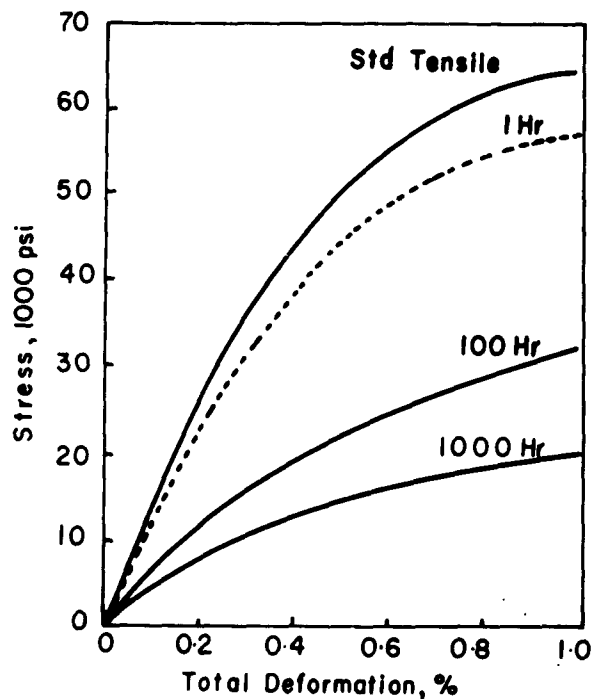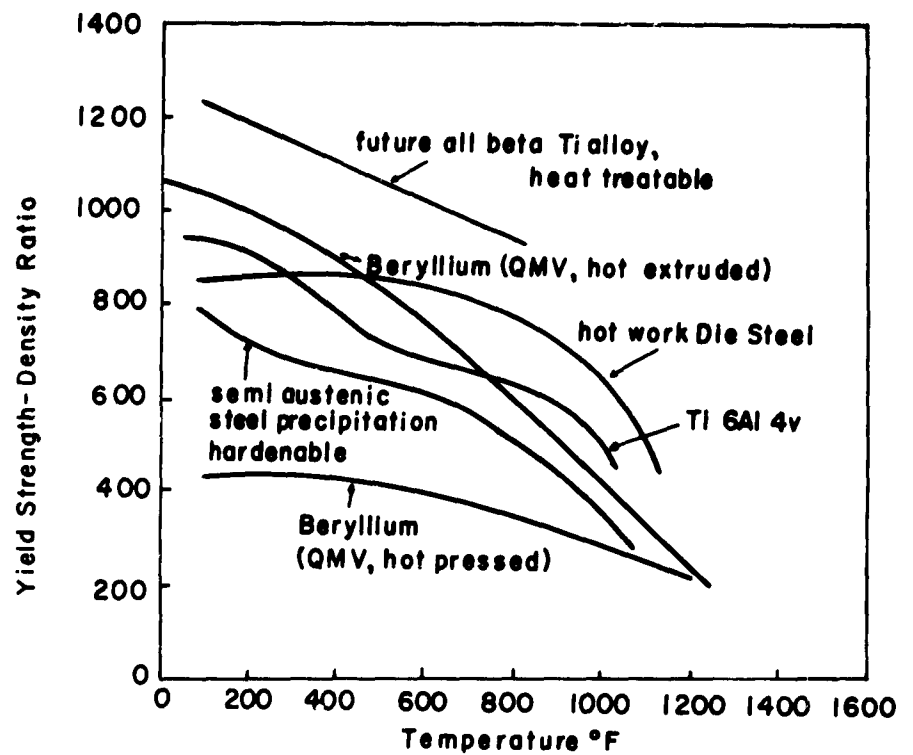


## Figure 17

Isochronous Creep Curves
for Ti-5 Al-2.5 Sn at
900°F.

The problem facing the parachute manufacturer is determining the proper stress level for a given length of time of exposure to the temperatures which we are faced with for this problem, namely, the temperature range of 1400 - 1500°F, for a period of 10 - 20 minutes.

Titanium is attractive to the aircraft designer because of its light weight, its corrosion resistance, and the high strength of its alloys. The stronger alloys have high strength weight ratios at room temperature, but it is at moderately elevated temperatures that the titanium alloys show their greatest advantage and have their widest applications. The titanium alloys bridge the temperature range between the lighter aluminum and magnesium alloys, and the much heavier high temperature alloys. Titanium alloys are used in the compressor section of jet engines for compressor blades, disks, and spacers. Applications of sheet alloys are becoming more important. Sheet is difficult to produce in the sizes and to the tolerance required by the aircraft industry, and many of the problems associated with the production of high strength in sheet remain to be solved. This is also true of the problems facing the wire manufacturer in titanium alloys.

Commercially pure titanium is relatively simple to fabricate and is used where ease of fabrication is a primary consideration and where high strength is not required. For more rigorous service conditions the high strength of titanium alloys are necessary. The sheet alloys available at present are furnished in the annealed condition with tensile strengths of about 130,000 psi, with elongations of 15%, reductions about 40%. The 6% aluminum, 4% vanadium alloy in sheet form is finding many applications in the form of forging, but is just becoming available in sheet form. This alloy is of the alpha-beta type and is therefore heat treatable to higher strength levels. In sheet form it will probably find its widest use in the heat treated condition.

In order to make high strength alloys available in sheet form the Department of Defense is sponsoring a sheet rolling program for the principal titanium alloy producers. The alloys selected for the program are those which can be heat treated to a high tensile level, and which can pass laboratory and pilot plant stages. The first phase of the program consists of melting large ingots of the selected alloys, and developing methods of rolling the ingots into a sheet which will meet reasonable tolerances as to thickness, flatness, and performance. The material will then be evaluated to determine compliance with target properties. Design data will be

obtained on the approved alloys as phase two of the investigation. This will include determination of all desired properties up to a 1000°F. The final phase of the investigation will be fabrication and evaluation of components made from sheet material. The first two phases are now in progress and results are encouraging, the project should lead to practical methods of producing high strength titanium alloy sheet and by proper evaluation of these results perhaps give an indication as to extending the limits of usefulness of extruded titanium ore.

The properties of aircraft alloys under various combinations of rapid heating and rapid loadings are being determined at Southern Research Institute under WADD sponsorship. Examples of these results on some of the light alloys are shown in the summary, along with properties of other alloys, as well as in Figures 18 and 19. In Figure 18 the specimens were held at temperature for one-half hour before the load was applied. It may be noted that at high strain rates the tensile strains are higher than at low strain rates. In Figure 19 the specimens were heated to a testing temperature in ten seconds. Load at high strain rate was immediately applied to one group of specimens but a second group was held at temperature for one-half hour before load application at the same rate. The tensile strain of the titanium and aluminum alloys was somewhat better at the higher temperatures after onephalf hour at temperature than after ten seconds, probably because of the aging which takes place in the specimens. As a concluding note a look at the future of the light alloys in aircraft and missile construction may be of interest. Many vehicles which travel faster than Mach 1 now utilize the light metals in large quantity. As speeds increase, aluminum and magnesium will become less attractive for exterior surfaces. Even titanium will eventually give way to the high temperature materials. This does not mean that the light metals will be of little use, for they will probably continue in use as internal structures where operating temperatures are lower. Materials will continue to be selected on the basis of the best combinations of the properties for specific application.

A complete and proper assessment of titanium requires knowledge of the physical and technological properties, as well as the structure and structural properties. A brief introduction to these areas will be given below. Table 3 summarizes the most important physical properties of titanium mean values being shown. Of fundamental interest is the low specific gravity of titanium which is at 4.5 grams per cubic centimeter about 60% of the specific
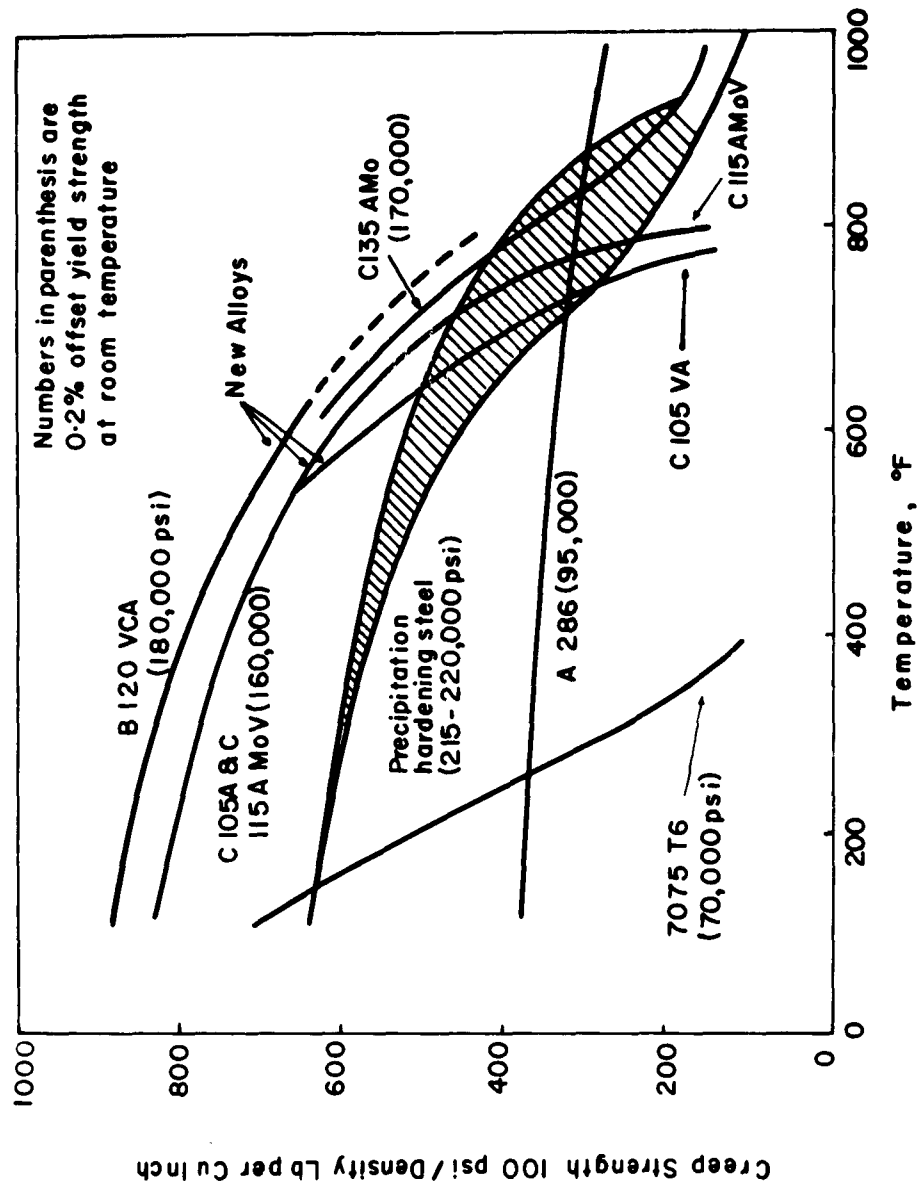
Figure 18 Creep Strength/Density vs. Temperature.
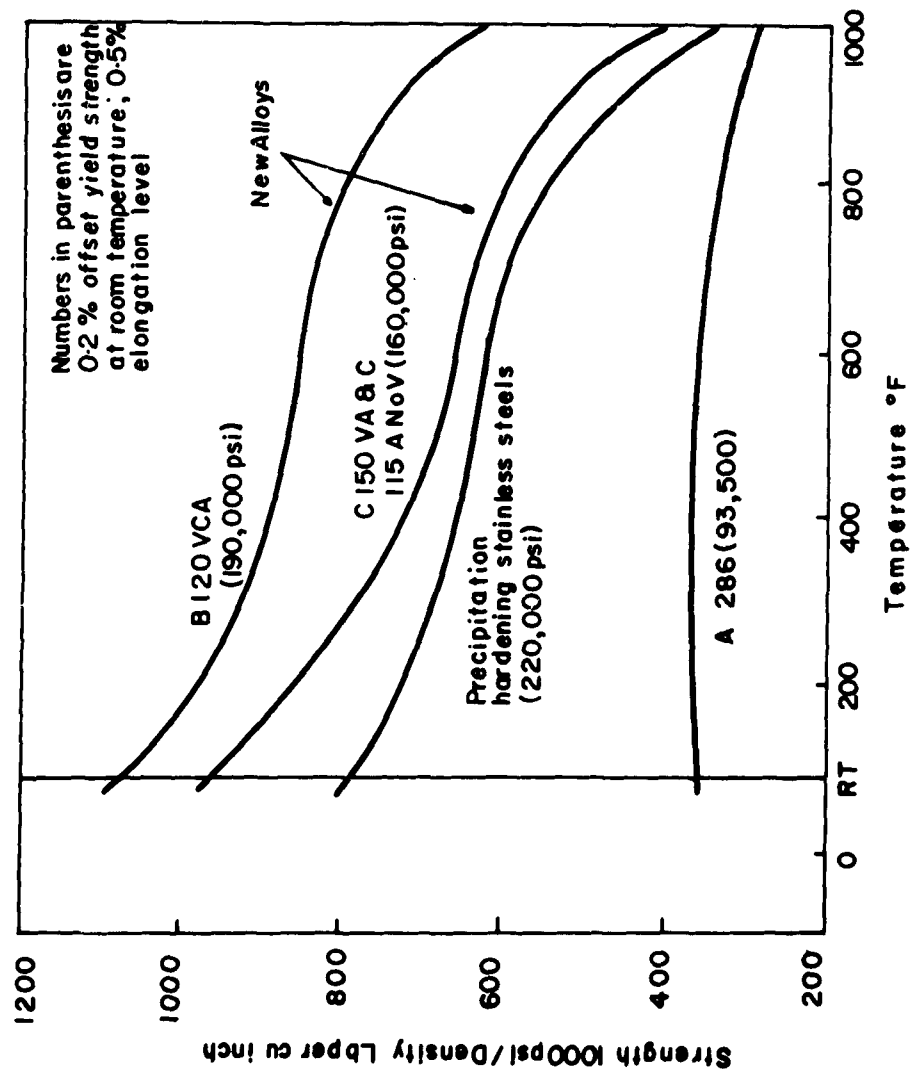
Figure 19  Creep Strength/Density vs. Temperature.

gravity of iron. The modulus of elasticity is only one-half of that of steel, but worthy features are the relatively low heat expansion and the low thermal conductivity which are of the same order of magnitude as for stainless steels.

## Table 3
### Physical Properties of Industrial Titanium

| Property | Industrial Titanium |
|---|---|
| Specific gravity (g/cm$^3$) | 4.5 |
| Crystalline structure | below 885° (for purest titanium): hexagonal closest spherical packing<br>above 885°:<br>body-centred cubic |
| Modulus of elast. (Kg/mm$^2$) | 11,000 |
| Speed of sound | 4,000 |
| Specific heat (cal/g°C) | 0.14 |
| Coefficient of thermal expansion (°C$^{-1}$) | $8.5 \times 10^{-6}$ |
| Thermal conductivity (cal/cm s°C) | 0.045 |
| Melting point ( °C) | 1,660° (Kroll titanium melts at about 1700°C, cf. in this connection, T.H. Schofield, A.E. Bacon J.Inst.Met. 82 1953/4, p. 167). |
| Specific elec. resistance at 20°C | $0.4 - 0.6 \quad \dfrac{\Omega \; mm^2}{m}$ |
| Magnetic behaviour | Paramagnetic |

**Surface Treatment of Titanium.** As a result of its marked tendency to galling and its poor wearing properties, in the case of metallic friction, the use of titanium is necessarily restricted. Its resistance to wear can be improved by surface treatment. Published works indicate as a very favorable method, surface hardening by means of nitrogen. In this case surface hardness of about 800 Vickers units is obtained. It is true that the hardness zone is small compared to that of nitrided steels. Furthermore, when nitriding with ammonia and simultaneous hydrogen absorption, there exists the danger of embrittlement. For this reason nitriding with oxygen is preferable. In this instance a high degree of purity is required in respect to the nitrogen used since even very slight oxygen admixtures will lead to the formation of easily flaking titanium oxide. Anodic oxidation makes it possible to coat titanium, in the same manner as aluminum, with thin tinted oxide film.

**Working of Titanium.** The forging of titanium merits greater attention since it is not yet in intermediate annealing. In cold rolling a texture is formed such that the (001) plane has an inclination of 25% to the direction of rolling, while the (1010) plane is in the direction of rolling. The cold rolling of wires, profiles, and the like has resulted in the tendency of titanium to seize at the tools. This presents some difficulties which, however, can be overcome by the application of metallic coating with suitable lubricants such as molybdenum, sulphide or also by slight oxidation. However, difficulties may be expected in the manufacture of fine, cold drawn wires for woven parachute application.

Deep drawing is also possible in the case of titanium, and its seizing between tool and work can be prevented. Here deformations up to about 40% are possible. Subsequently cold annealing must again be undertaken. In particular working must be performed with low declamation velocity in order to avoid cracks. In which case, generally speaking, only hydraulic presses can be used. Satisfactory deep drawing values are obtained by heating to 200 to 400°C. Such heating also obstructs the marked tendency of titanium to spring back. It is interesting to note, here, that if one precludes the use of atmospheres or conditions under which welding is done—which would include an atmosphere of oxygen—that there is very little difficulty in welding titanium sections. It is of interest though to make note that it is not possible to weld titanium with other materials such as steel since in such cases brittle transitional alloys are formed. Soldering, therefore,

acquires a certain importance. Since with the usual soldering alloys and fluxes, soldering is unsatisfactory pure silver alloys with high silver content are used for the purpose. When soldering according to the traditional methods it is scarely possible to avoid oxidation so that it is desirable to apply heat inductively under a protective gas atmosphere. If in certain cases soft soldering is necessary -- as in, for example, fixing electrical contacts, the titanium must previously be covered with a layer of another metal, for example, a copper layer applied electrolytically. The stability of such combinations is limited by the adhesiveness of the covering layer of the titanium which is essentially of a mechanical character. Roughening of the titanium section, for example, by sand blasting leads to an improvement in adhesion.

## Titanium Alloys-Basic Types

Alpha Alloys. Alpha alloys have an essential constituent, aluminum addition. Since the beta phase cannot be super-cooled by quenching, and as a result no reactions in solid state are to be anticipated in tempering. These alloys present the advantage of stability even at high temperatures. On the other hand, these properties are capable of being influenced only to a limited extent by heat treatment. Alpha alloys have relatively good strength for use up to 600°C. Figure 20 shows the dependence of hardness on the test temperature for various titanium alloys. From this it will be seen that in the case of Titanium-Al alloy, even at temperatures of 550°C, a relatively high hardness is still maintained. Figure 21 shows that the hardness can be still further increased by supplementary alloy addition. The alpha alloys are, moreover, relatively insensitive to impurities when annealed in air up to 1100°C. A high deformation temperature, can therefore be selected. In addition, alpha alloys are marked by fairly good weldability.

Alpha-Beta Alloys. Alpha-beta alloys have good ductility and at the same time possess a strength which is about double that of unalloyed titanium. They are more easily worked than alpha or beta alloys and present the further advantage, as a result of heat treatment, of obtaining high strength values. In this connection, quenching with subsequent tempering or isothermal heat treatment, is possible. The alpha-beta alloys have the disadvantage of not being stable at high temperatures since, in the case of protracted annealing, the beta component can undergo eutectoid decomposition with ensuing possible embrittlement. The upper temperature level limit for their use is about 450°C, at higher temperatures there is a marked decrease in strength.
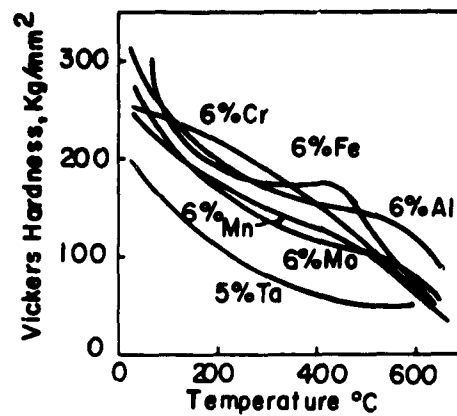
**Figure 20  Heat Hardness of Some Binary Titanium Alloys.**
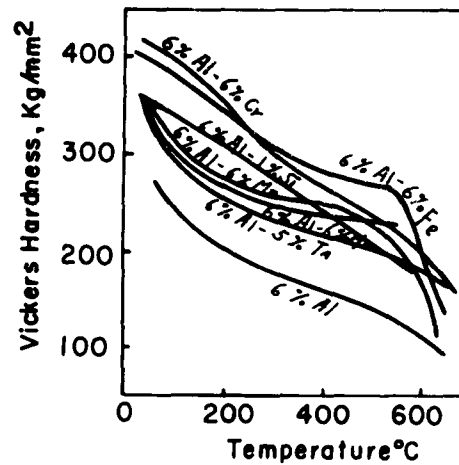


**Figure 21  Heat Hardness of Some Ternary Titanium Alloys.**
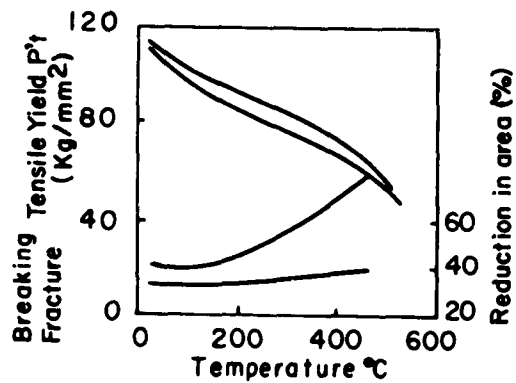


**Figure 22  Mechanical Properties of an Alloy - Ti-4%, Al-4%, Mn.**

Figure 22 shows the temperature dependence of the mechanical properties of Ti 4%.Al 14%,manganese alloy. Alpha-beta alloys have not such good welding properties as pure alpha alloys. Unsatisfactory heat treatment may further reduce the ductility as a result of grain coarsing.

Beta Alloys. The content of added elements required for stabilization of the beta phase varies according to the alloy system. Thus, for example, about 11.5% molybdenum, 15% V, 6.5% Cr. or 6.5% Mn, are required to stabilize particular binary alloys.

Unstable beta alloys after quenching have medium strength, good ductility, and can be tempered to higher strength values with simultaneous reduction of ductility. The strength can be increased by isothermal heat treatment. For a number of alloys, time transformation diagrams are already similar to those of the alpha-beta alloys. They have the disadvantage in fairly long tempering and a temperature between 200 and 400°Cof becoming brittle.

Stable beta alloys possess high ductilities and good strength value. They can be used at a fairly high temperature but are not capable of heat treatment. One disadvantage of beta alloys is their great sensitivity to impurities during preparation hot working. The alloying possibilities are in a state of development so that further considerable improvement may be anticipated. It is, however, already clear that taking into account the specific gravity, titanium alloys may be superior at temperatures of 550°C to stainless steel, in regard to creep strength. Table 4 shows the mechanical properties of some commercial alloys.

## Table 4

### Mechanical Properties of Various Ti Alloys

| Property | 5Al;2.5Sn | 4Mn:4Al | 3Al:5Cr | 3Mn;1Fe;1Cr;1V;1Mo |
|---|---|---|---|---|
| Tensile Strength $(kg/mm^2)$ | 90 | 113 | 117 | 92-134 |
| Yield Point or 0.2 limit $(kg/mm^2)$ | 85 | 110 | 112 | 92-113 |
| Elongation before Fracture 85% | 15 | 13 | 14 | 10-20 |
| Brinnell Hardness H330/5 | 180 | 340 | 330 | 290-400 |

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A.    METALS (Continued)

2.    Light Metals

Beryllium

Beryllium in the sense of its mechanical properties is an
extremely interesting metal.  Its density is very low, being
0.066 lbs. per cubic inch.  It has a melting point of 2350°F, a
modulus of 40 x 10⁶ psi and a tensile strength at room temper-
ature between 40 and 80 thousand psi depending upon the fabric-
ation techniques employed in its manufacture.  Ellis' papers on
the Development of Beryllium for Nuclear Reactor Applications
furnish the following background (26).

Stress rupture and creep data on beryllium are reported by
Kaufmann (11).  These relate to hot extruded, so-called pebble
metal ingots tested in the range of 400°C to 1100°C.  The results
of these investigations are produced in Figures 23, 24.  At 600°C,
the stress for rupture 100 hrs. and 1000 hrs. is approximately
2500 lbs. per square inch and 1500 lbs. per square inch respec-
tively.  There are no corresponding data published on flake ingot
or on powder material in the extruded or rolled conditions.  It
is of interest, however, that a decrease in rate of strain at
temperatures of 200°C to 600°C causes a reduction in tensile
strength and elongation with hot pressed powders.  This is shown
in Figure 25 (after Beaver et al.).  A similar effect is shown in
Figures 26 and 27, by Kaufmann, for extruded pebble metal ingot.

While the potential properties for the metal beryllium are
excellent, there are many practical difficulties connected with
its production.  Beryllium ingots are produced by high frequency
vacuum induction melting and casting using a beryllia crucible, a
graphite or a mild steel mould and a bottom pouring technique.
Vacuum melting and casting reduces the halide and volatile metallic
contents.  American pebble contains 99.5% beryllium with 0.05%
manganese, 0.11% iron and 0.06 aluminum as the main metallic
impurities.  The fluoride content is not usually given.  Beryllium
oxide content is generally 0.2% or less. Flake material is very
slightly higher in purity.

Ingot beryllium is extremely brittle at room temperature and
exhibits a coarse grained columnist structure.  Beryllium also
exhibits hardness and isotropy.  These qualities cause high tool
wear and relatively poor machined finish, the latter being due to
individual grain detachment and to mosaic patterned formation. The
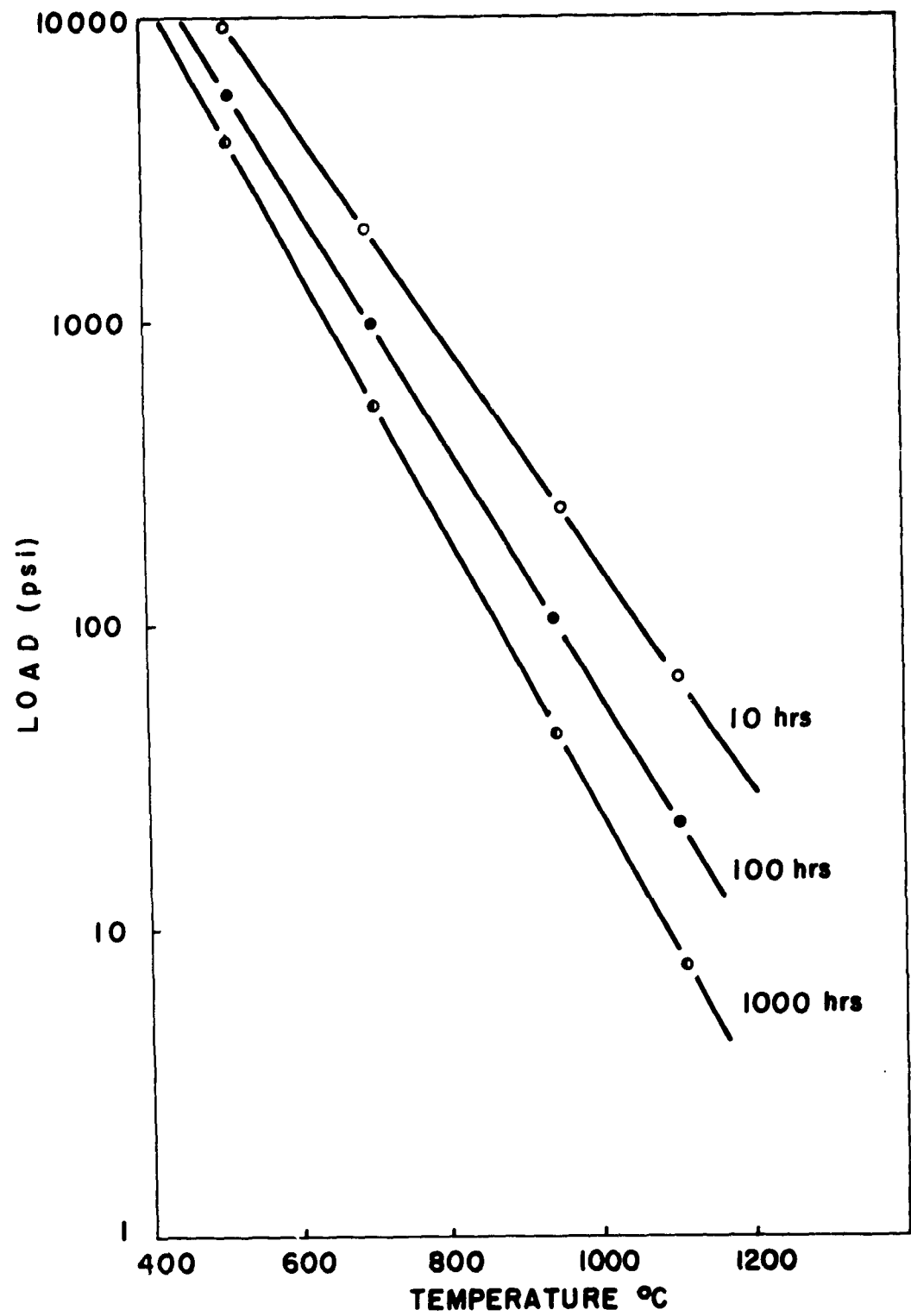
Fig. 23 Beryllium stress versus temperature curves for arbitrary rupture times. (After Kaufman, 11).
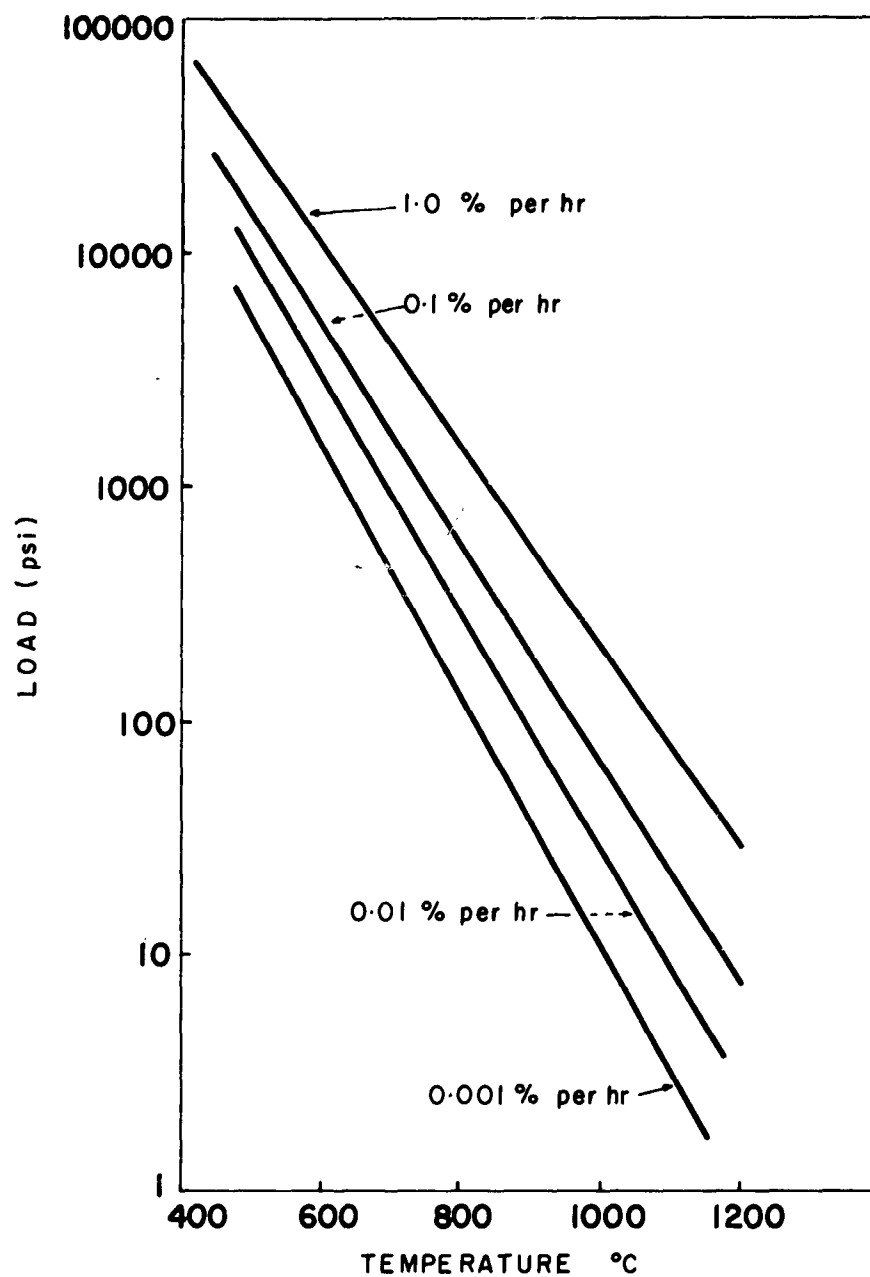
Fig. 24  Beryllium stress versus temperature curves
for arbitrary creep rates.  (After Kaufman, 11)
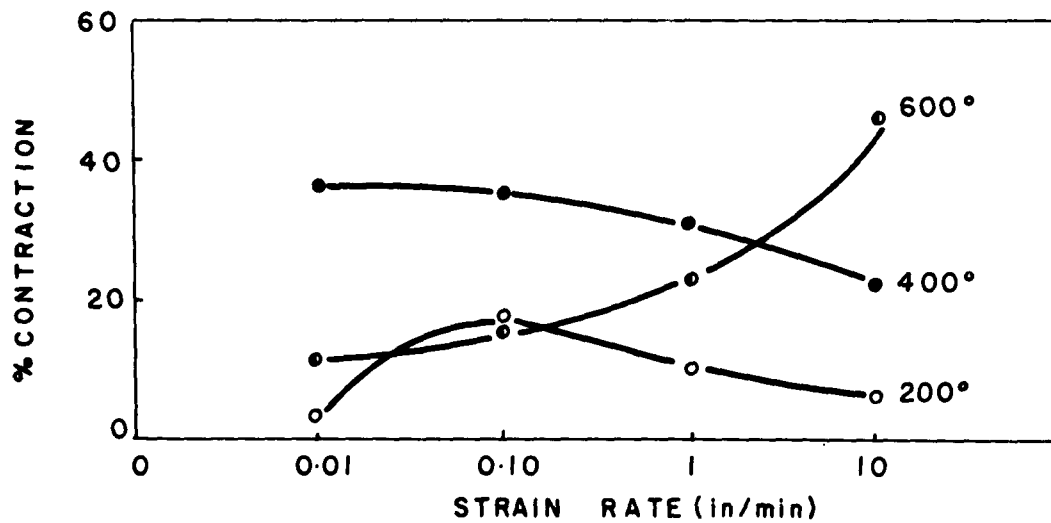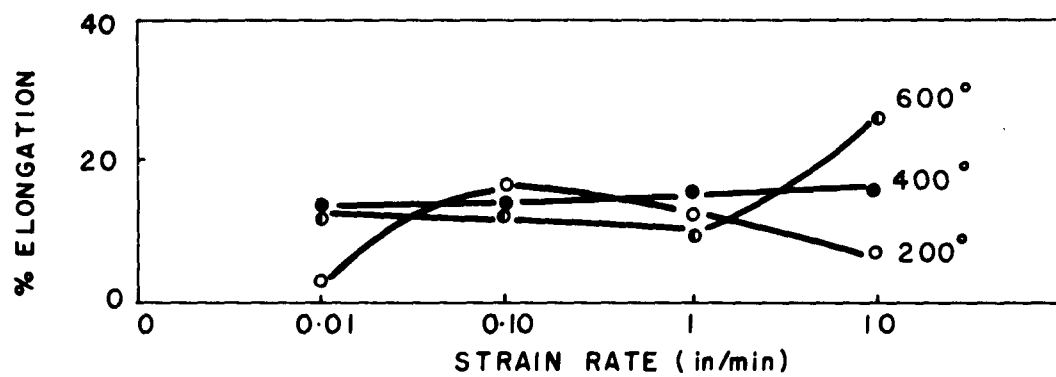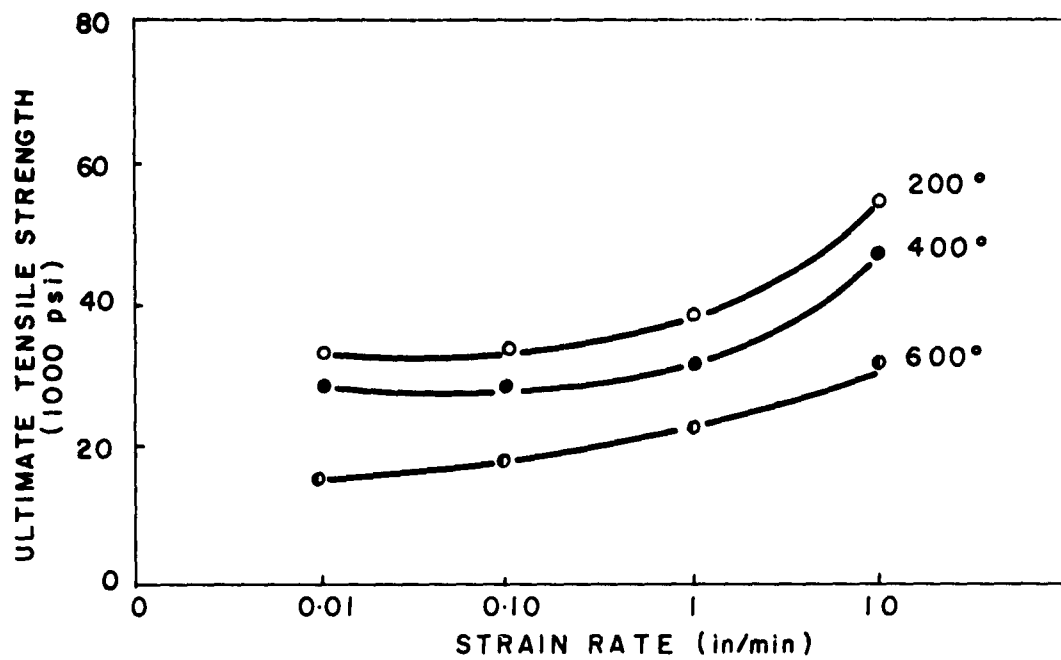
Fig. 25  Effect of strain rate on the elevated temperature
tensile properties of vacuum hot pressed beryllium, lot
Y-4522-HP.  (After Beaver 15).
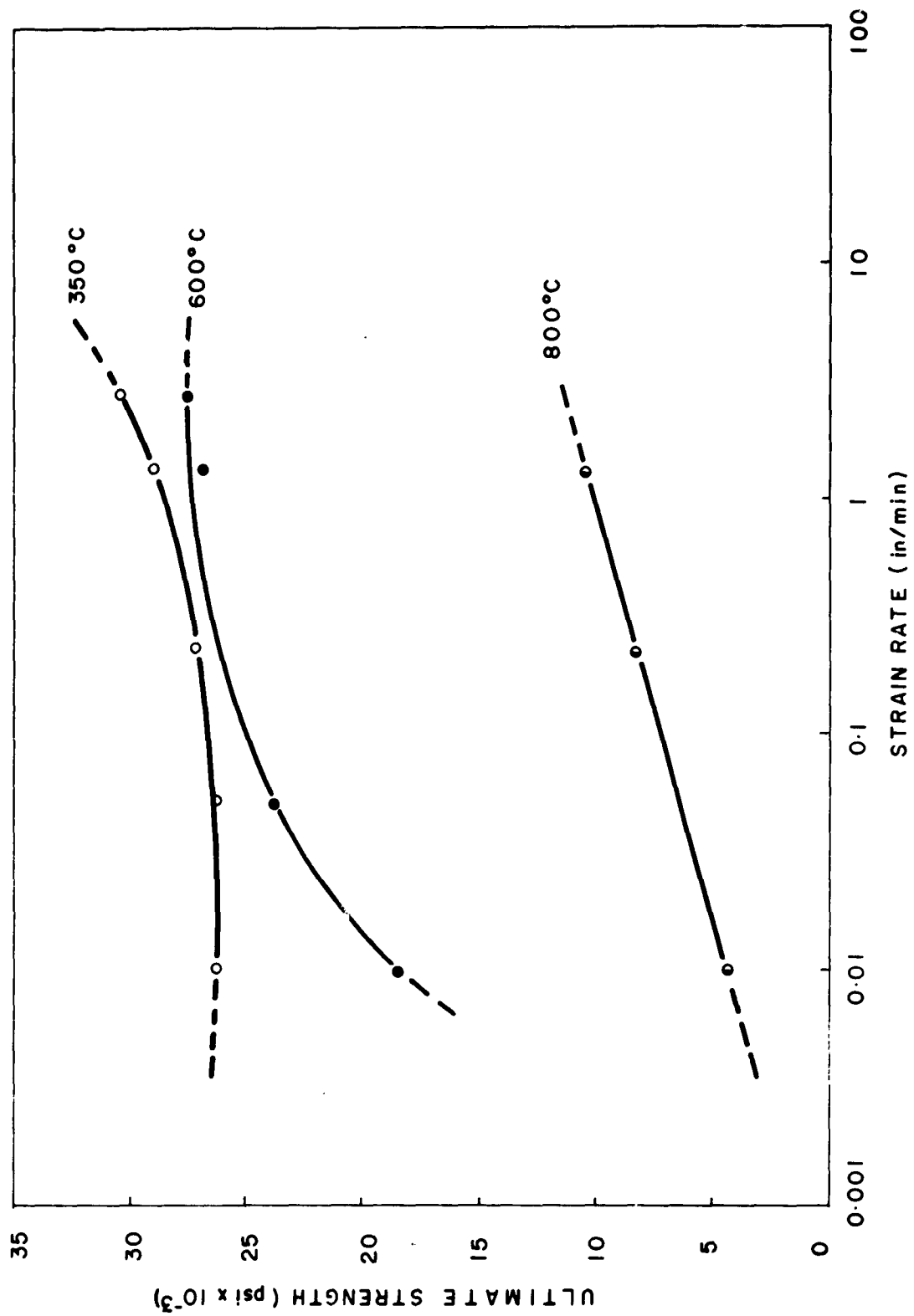
Fig. 26 Effect of strain rate on ultimate strength of beryllium at various temperature. (After Kaufman, 11)
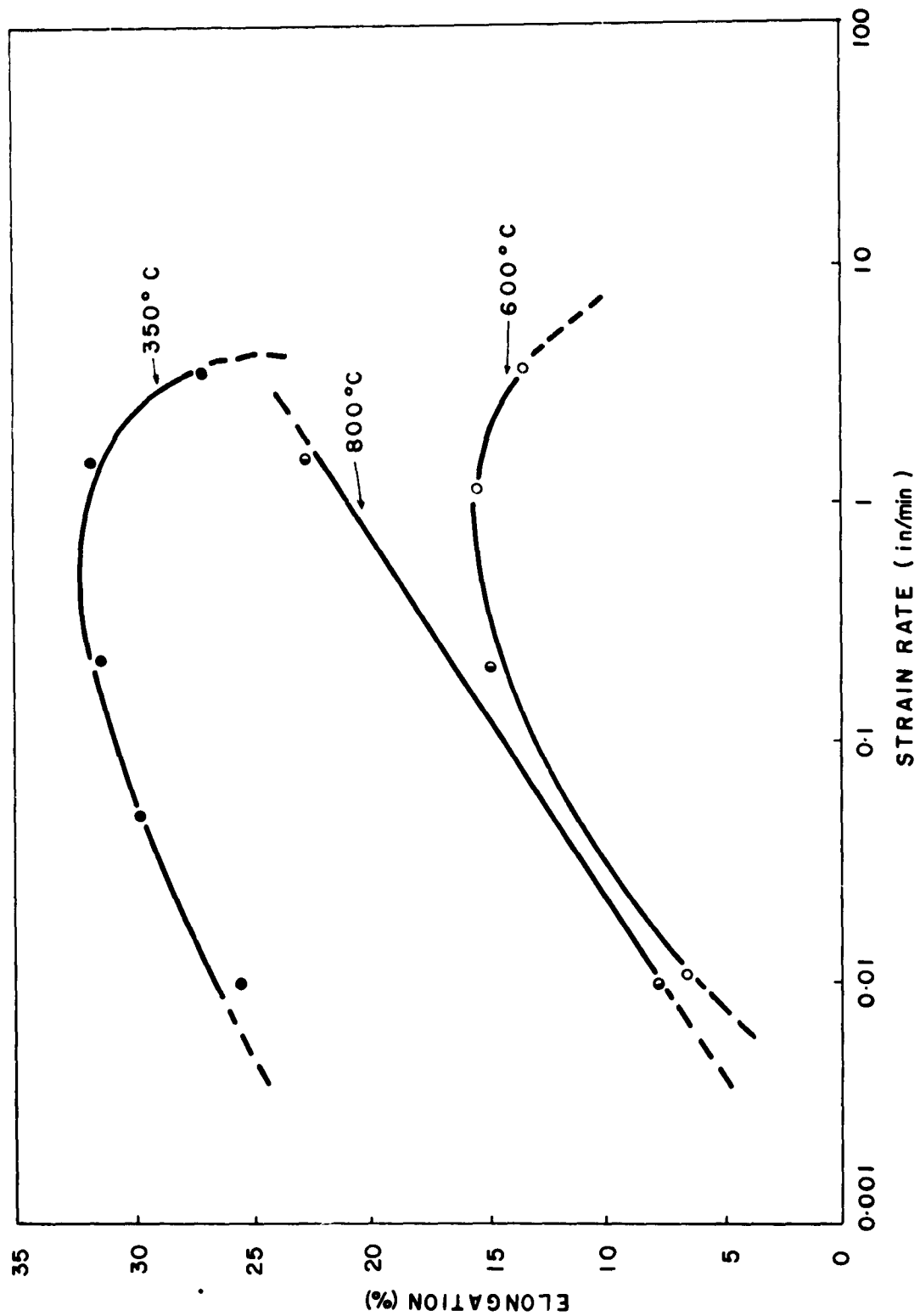
Fig. 27 Effect of strain rate on elongation of beryllium at various temperature. (After Kaufman, 11)

main difficulty in ingot production is the elimination of unsoundness. Ingot beryllium is hot short. Liquid beryllium possesses a relatively high surface tension and fluidity, consequently excessive solidification rates cause formation of intercolumnar cracks and pipes due to the low fluidity and poor feeding. On the other hand, the use of slow solidification rates is precluded by the accentuation of grain coarseness, thus intermediate solidification rates must be used. It is extremely difficult, at the present time, to produce large machine blocks for nuclear reactor use, and the metal is very unattractive for fabrication to sheet and tube components, much less wire. Up to the present time, no success has been reported in grain refinement by alloying metal additions by mould vibration or by variation in melting practice.

Investigations have been made of beryllium alloys. Beryllium rich solid solutions, which are few, are of limited solubility and are terminated usually by intermetallic compound formation. Thus the alloys are brittle in both the cast and fabricated conditions.

Beryllium powder is also produced commercially. Vacuum cast pebble metal ingots are turned to chips in a cutting operation and these chips are then milled to a powder. The powder is discharged onto a screen following which it is recycled and blended for mesh size. Beryllium powder may then be consolidated by die pressing to a pressure of roughly 60 to 80 tons per square inch followed by vacuum sintering at 1125°C to 1175°C. It may also be hot pressed at 1100°C maintaining the pressure for long times, up to 24 hrs. Pressure used is about 150 lbs. per square inch. It is also hot pressed at higher loads, somewhat lower temperatures. (See Figure 28).

Forging of ingots for grain refinement prior to extrusion or rolling is not normally possible, as the ingots fail by cracking. Bars of round or rectangular section and tubes are produced by extrusion of a sheathed ingot and by consolidation of powder beryllium at 1050°C. Reductions may be of the order of 30 to 1. The extruded surface of the ingot is rough in comparison to the surface of the extruded powder. Warm extrusion is sometimes carried out at 450°C and requires the use of the suitable sheath or surface coating which will act as a barrier and lubricant. Sheet may be produced from ingot or powdered billet by hot sheath rolling at 950°C with 10% to 15% reductions and interpass reheating. After a total hot reduction of 75% to 80% in thickness, finish rolling can be carried out at temperatures down to 450°C. Beryllium in general has low ductility and develops maximum properties in the direction of working. The limited modes of deformation that are
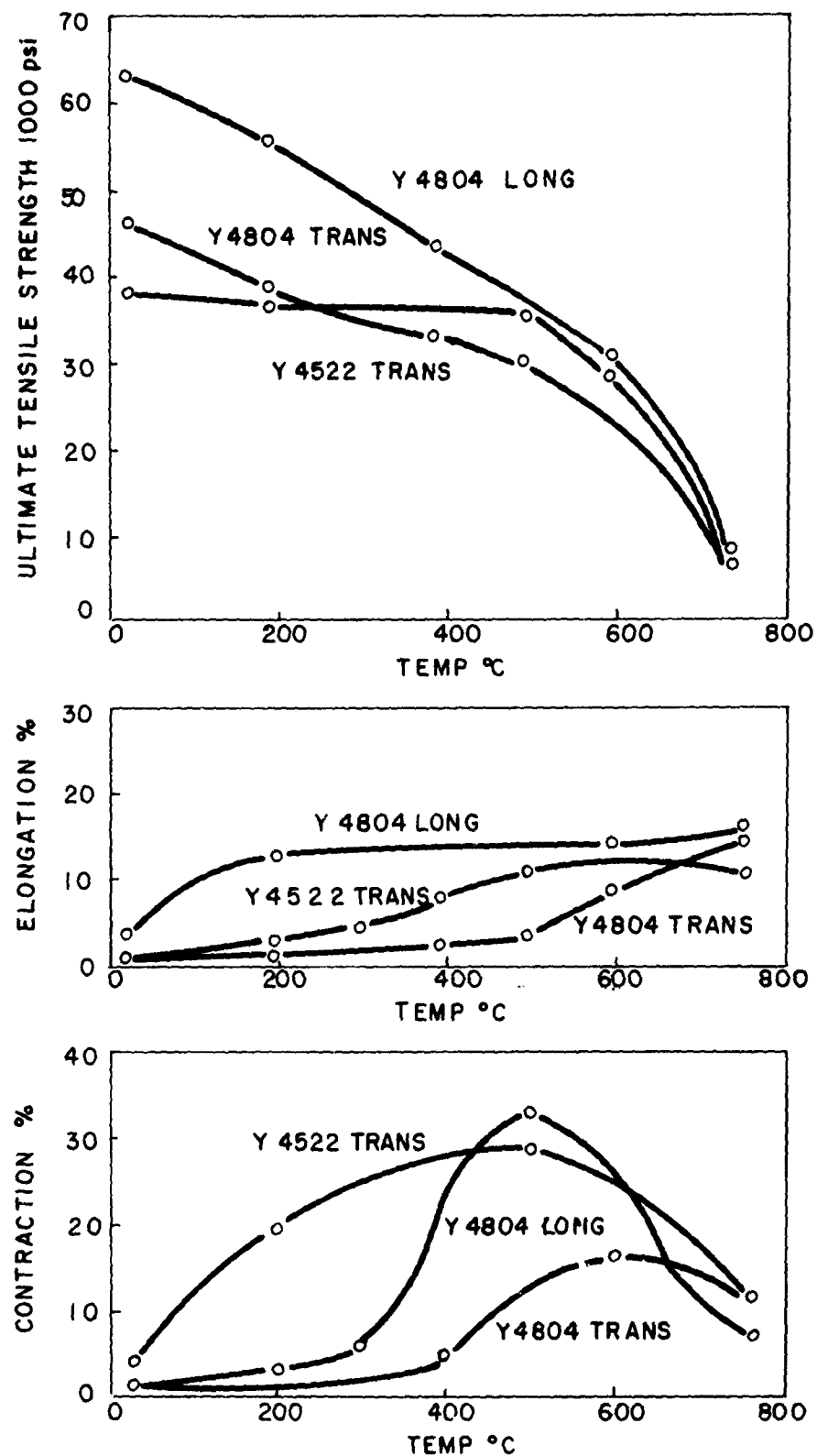
Fig. 28 Comparison of longitudinal and transverse tensile
properties of extruded QMV beryllium at elevated temperatures.
Vacuum hot pressed and extruded from 2¼ to 1½ inches diameter
at 425 °C.

available in a practical sense result in marked anisotropy of properties with relatively poor transverse strength and ductility. The attainment of maximum properties in two directions is, therefore, dependent on the development by fabrication control of the suitably oriented structure. This may be obtained in sheets by alternate cross rolling. The realization of the same degree of orientation controlling tube production is not possible because of the uni-directionality of the tube forming process.

Ellis (26) has provided a worthwhile summary of the mechanical properties of beryllium in different forms and following varying treatments. Pertinent graphical relationships are shown in Figures 29-32 following. Figure 29 gives a comparison of the tensile strength in the longitudinal direction of various forms of fabricated beryllium as a function of temperature (4). Figure 30 compares the elevated temperature tensile elongation in the longitudinal direction of various fabricated forms of beryllium (4). Figure 31 shows the longitudinal and transverse tensile strength and elongation of hot extruded powder as a function of temperature (15) and Figure 32 shows the effect of grain size on the longitudinal tensile strength and elongation of hot extruded powder (15).

Beryllium is also a difficult metal to weld or braze because of its cold brittleness, hot shortness and the ease with which it oxidizes. Fusion welding has not been successful, in general, but some success has been accomplished by use of a bare beryllium filler rod with a tungsten electrode, an inert gas shield and a DC current (4). Pressure welding at high pressures and high temperatures has also been reported (4). The main difficulty is the provision of suitable jigs which tend to preclude the pressure welding of awkward shapes. Another difficulty is that the high pressures and temperatures required for successful joints are not compatible with the joining of thin sections if intricate design. In the United States, it is considered that brazing is the most satisfactory method of joining beryllium to itself and other metals (4).

Beryllium is abrasive and causes relatively high tool wear in machining (4). The metal can be turned, milled, drilled, reamed or ground under conditions somewhat similar to those for cast iron, but it is difficult to saw. Dry cutting conditions with carbide tipped tools are preferred.

The metal beryllium does not oxidize appreciably below 600°C although fairly rapid oxidation commences between 800°C and 850°C.
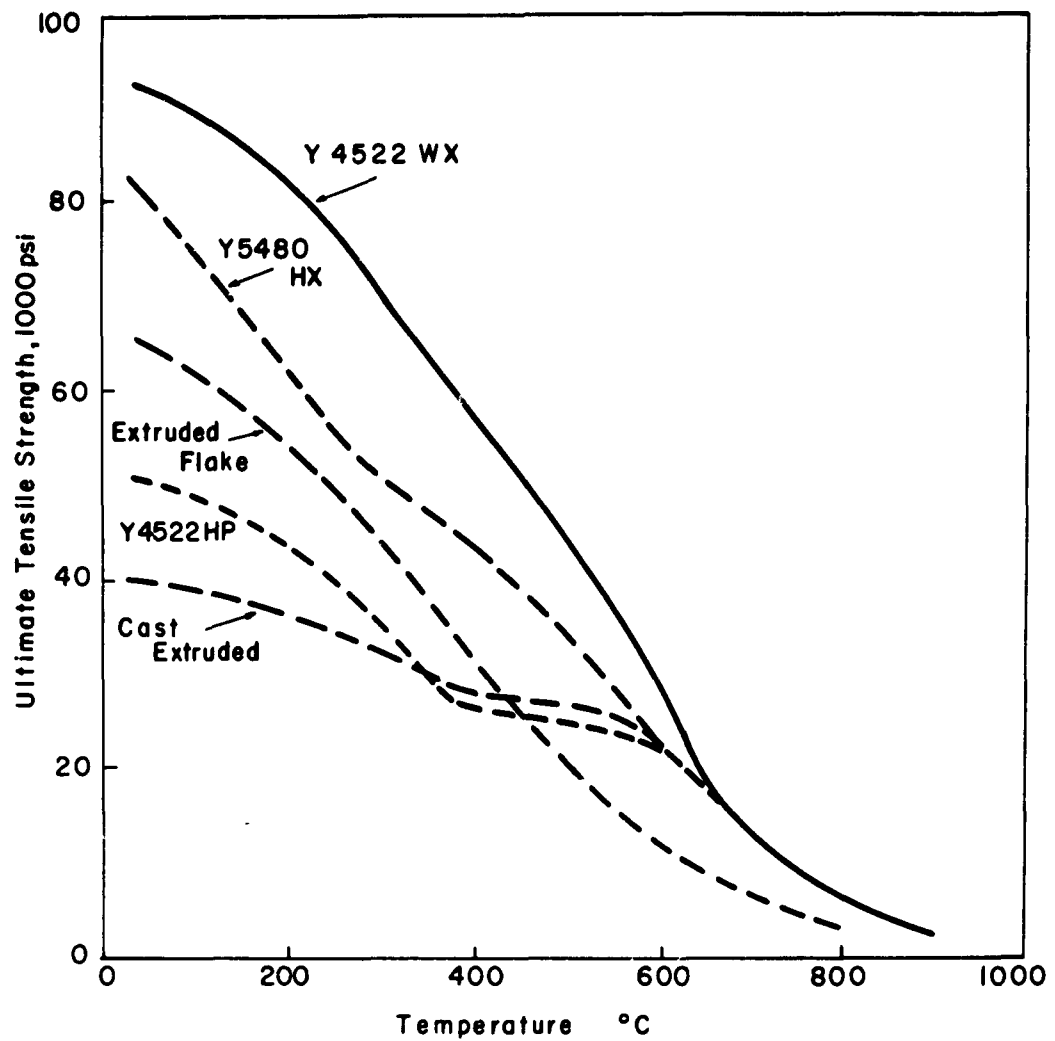
Fig. 29 Comparison of elevated temperature tensile strengths
exhibited by various types of beryllium.
(White and Burke, 4)
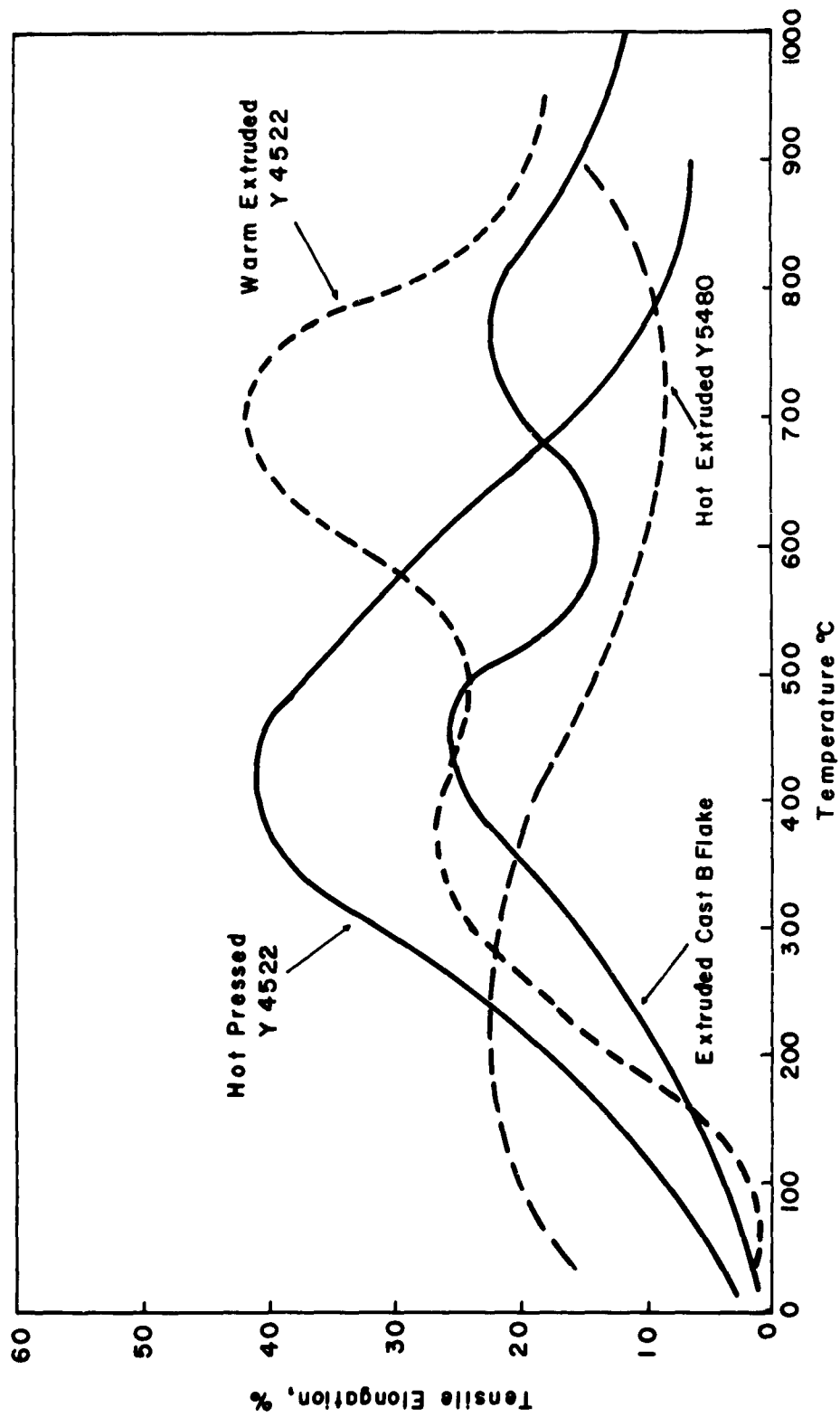
**Fig. 30** Comparison of elevated temperature tensile elongation exhibited by various types of beryllium. (White and Burke, 4)
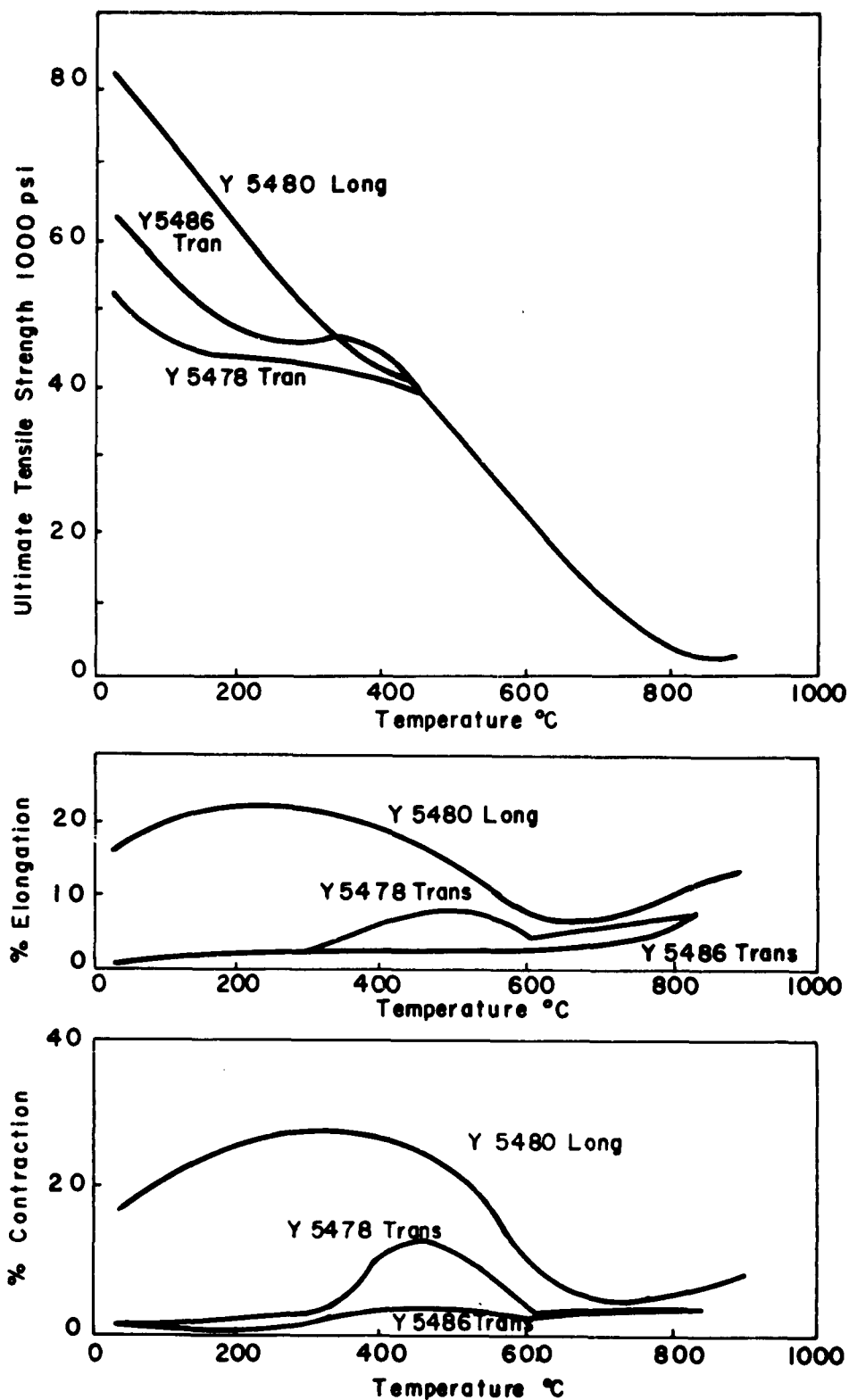
Fig. 31    Comparison of longitudinal and transverse tensile
properties of hot extruded QMV beryllium at
elevated temperatures. (After Beaver 15).
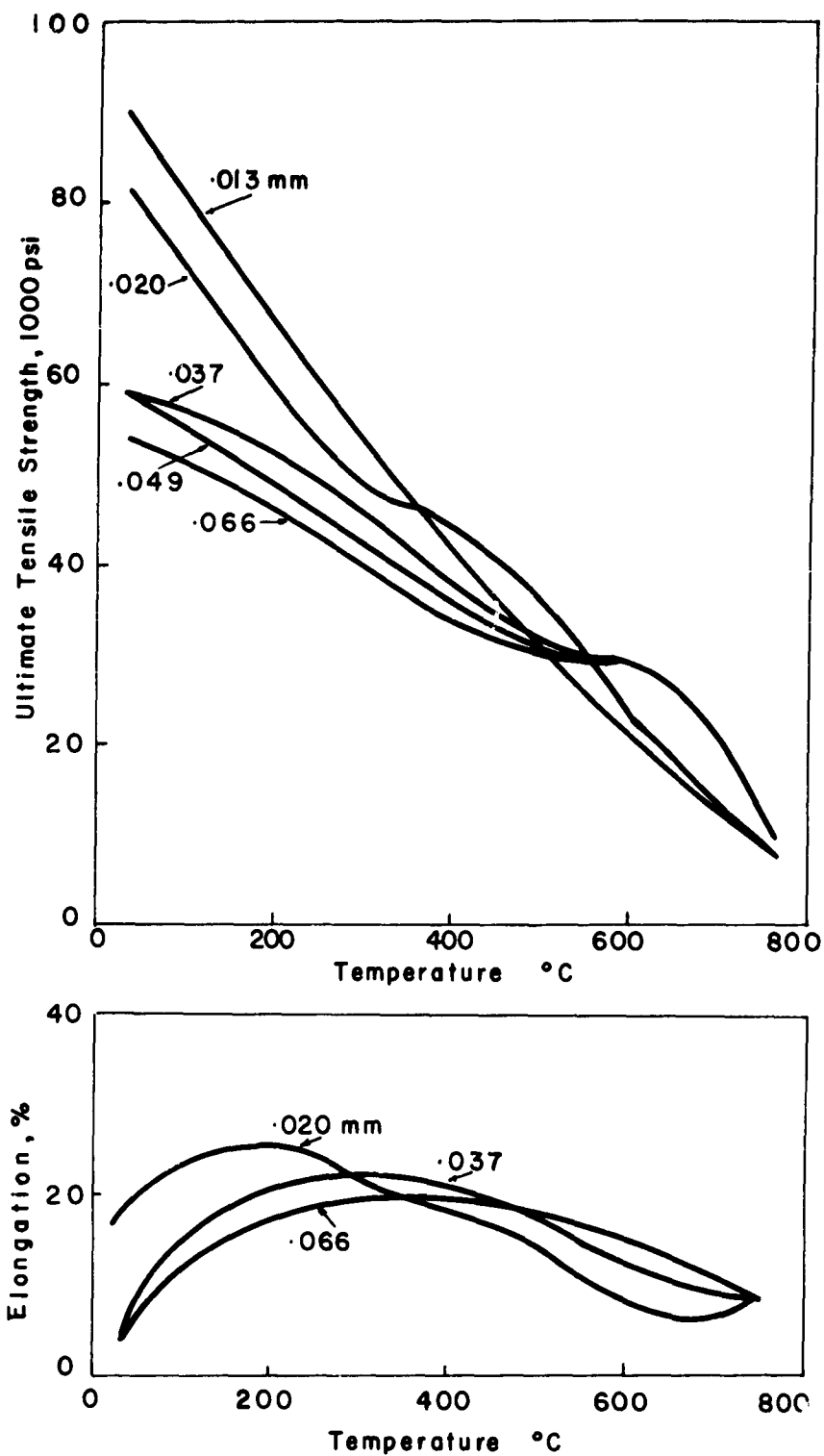
Fig. 32 Effect of grain sizenon elevated temperature
tensile properties of hot extruded QMV beryllium.
Grain size in average diameter. (After Beaver 15)

The Russians report the development of protective coatings for high temperature use (3). There is some atmospheric corrosion of beryllium at room temperature and this appears to be connected with the hydrolysis of carbide and halide inclusions in the metal. The water corrosion resistance of beryllium appears to be erratic while that of the powder metal is better than the ingot.

In addition to production fabrication difficulties and cost, beryllium presents a severe health hazard. In any case, problems of formability and cost probably preclude its use for parachute drag devices for the immediate future and perhaps for several years to come.

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A. METALS (Continued)

### 3. Super Alloys - Introduction

Superalloys will undoubtedly be called upon to furnish the heat resistant materials for the space vehicles, since data thus far released indicates that all but certain "hot spots" are within the capabilities of the superalloys of today. The hot spots will either be protected by "cooled" superalloys or by coated refractory alloys.

Several methods can be used to classify superalloys. On the basis of chemical composition, they would be classified into six groups.

1. Cr-Ni-Fe alloys - used in hot-cold work, warm work conditions when strengthened by carbide forming elements. Alloys containing aluminum and titanium are heat treatable. This category also alloys based on austenitic stainless steel compositions. (16-25-6, 19-9DL, etc)

2. Cr-Ni-Co-Fe alloys - normally used in heat treated (solution treated and aged) condition. (N155, 5590, etc)

3. Wrought cobalt base alloys - used in heat treated condition. (S816, L605)

4. Cast cobalt base alloys - generally used in the as-cast condition. (HS21, X-40, HS31, etc)

5. Wrought nickel base alloys - strengthened by additions of Ti plus Ai to cause precipitation hardening. (M252, Waspaloy, U500 etc)

6. Cast nickel base alloys - also strengthened by additions of Ti plus Al. (GMR235, Nicrotung 1800, Waspaloy, Inco 713, HS8294, etc)

An extensive listing of compositions for such alloys is given in Table 5, along with typical properties (also Figure 33).

Unfortunately, data for extremely short time periods, limited strains of the type which will govern the use in space vehicles is not too widely available. However, the short time properties of general aircraft structural materials are shown in the several

## Table 5 Superalloys

| Alloy | C | Mn | Si | Cr | Ni | Co | Mn | W | Cb | Ti | Al | Fe | Other | 1200 F 100 | 1200 F 1000 | 1350 F 100 | 1350 F 1000 | 1500 F 100 | 1500 F 1000 | 1600 F 100 | 1600 F 1000 | 1800 F 100 | 1800 F 1000 | Probable Patentee |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GROUP I—CHROMIUM NICKEL IRON ALLOYS** | | | | | | | | | | | | | | | | | | | | | | | | |
| 19-9WMo | 0.10 | 0.50 | 0.60 | 17.0 | 9.0 | | | 1.30 | 0.44 | 0.40 | | 68.0 | — | 41.0 | 34.0 | 28.5 | | 11.0 | | | | | | Universal-Cyclops |
| 19-9DL | 0.30 | 1.10 | 0.60 | 17.0 | 9.0 | | | 1.20 | 0.40 | 0.30 | | 68.0 | — | 52.0 | 38.0 | 28.0 | 19.0 | 17.0 | 10.0 | | | | | Universal-Cyclops |
| 19-9DX | 0.30 | 1.00 | 0.65 | 17.2 | 9.0 | | | 1.20 | | 0.55 | | 68.0 | — | 52.5 | 42.4 | | | | | | | | | Universal-Cyclops |
| 19-9WX | 0.11 | | 0.70 | 20.5 | 8.5 | | | 1.50 | 1.30 | 0.20 | | 65.0 | — | | | | | | | | | | | Universal-Cyclops |
| Inco 625 | 0.05 | 1.20 | 0.25 | 5.5 | 25.0 | | | | | 2.30 | 0.70 | 35.0 | — | | | | | | | | | | | INCO |
| Inco 901 | 0.05 | 0.48 | 0.25 | 12.8 | 43.0 | | | | | 2.43 | | Bal. | — | 80.0 | | | 18.0 | 10.0 | | | | | | INCO |
| 17-14CuMo | 0.15 | 2.00 | | 16.0 | 15.0 | | 5.08 | 1.40 | 1.05 | | | Bal. | 0.15Nb | | | | | | | | | | | Babcock & Wilcox |
| GT-45 | 0.12 | 0.75 | 0.50 | 15.9 | 14.1 | | 2.50 | | 0.45 | 0.25 | | Bal. | 3.0Cu | 43.0 | 37.5 | 26.5 | 16.5 | 12.0 | | | | | | ARMCO |
| Timken 16-25-6 | 0.10 | 1.35 | 0.50 | 16.1 | 25.0 | | 6.00 | | | | | 50.0 | 0.15N | 45.0 | 34.0 | 25.0 | 13.5 | 9.0 | | | | | | Timken |
| Discaloy 24 | 0.03 | 0.84 | 0.92 | 13.1 | 25.5 | | 2.83 | | | 1.83 | 0.10 | Bal. | | 53.0 | 41.0 | 32.0 | 15.0 | | | | | | | | Westinghouse |
| HS-88 | 0.07 | 1.30 | 0.30 | 12.5 | 15.0 | | 2.00 | 0.60 | | 0.60 | | Bal. | 0.15B | 59.0 | 49.0 | 42.0 | 25.5 | 16.0 | 13.5 | | | | | Haynes Stellite |
| Conservaloy | 0.04 | 8.50 | 0.40 | 22.0 | | | | | | | | Bal. | 0.35N | | | | | | | | | | | Allegheny Ludlum |
| A-286 | 0.05 | 1.35 | 0.95 | 15.0 | 26.0 | | 1.75 | 1.00 | | 2.00 | 0.20 | Bal. | 0.3V | 61.0 | 46.0 | 35.0 | 18.0 | 13.0 | 8.5 | | 5.2 | | | Allegheny Ludlum |
| Gimut | 0.25 | 1.00 | 1.00 | 15.0 | 24.0 | | 2.00 | 4.00 | | 2.25 | 1.00 | Bal. | | | | | 21.0 | 13.6 | 7.7 | | | | | Allegheny Ludlum |
| S-497 | 0.40 | 1.50 | 0.80 | 14.0 | 20.0 | | 4.00 | 4.00 | 4.00 | | | 51.0 | | 43.0 | 36.0 | 26.0 | 21.0 | 18.0 | 14.0 | 13.3 | | | | Allegheny Ludlum |
| S-588 | 0.42 | 1.50 | 0.40 | 18.0 | 20.0 | | 4.00 | 1.30 | 1.00 | | | Bal. | | 41.0 | 30.0 | 25.0 | 18.0 | 15.0 | 10.0 | | | | | Allegheny Ludlum |
| 4SA | 0.25 | 4.00 | 0.40 | 18.0 | 3.0 | | 1.30 | 3.20 | 1.20 | | | 68.0 | | 50.0 | 39.0 | 22.5 | 12.5 | | | | | | | Crucible Steel |
| EME | 0.10 | 0.50 | 0.70 | 17.0 | 12.0 | | | | | | | 63.0 | 0.15N | 44.0 | 35.0 | 22.0 | | | | | | 1.6 | | Rinvale |
| Incoloy | 0.10 | 1.00 | 0.60 | 20.5 | 32.0 | | | | | 1.00 | | Bal. | | 30.0 | 18.0 | 15.0 | 10.8 | 5.7 | 3.6 | | | | | INCO |
| Incoloy T | 0.35 | 1.30 | 1.17 | 14.7 | 32.0 | | | 4.00 | | | | Bal. | | 33.0 | 26.1 | 20.1 | 14.7 | 10.5 | 7.0 | | | | | INCO |
| ATV-3 | | | | | 24.4 | | | | | | | | | | | | | | | | | | | |
| Gamma Columbium | 0.40 | 0.84 | 0.02 | 15.2 | 24.0 | | 4.10 | | 2.20 | | | Bal. | | | 36.0 | | 11.0 | 10.8 | 8.0 | | | | | ML-3-100(C) |
| KL-3-100(C) | 1.85 | 1.50 | 0.50 | 28.0 | 35.0 | | 8.00 | | | | | Bal. | 0.15B | 65.0 | 56.0 | 41.0 | 32.0 | 24.0 | 15.0 | 16.0 | 10.5 | 7.0 | | INCO |
| Turbaloy 13 | 0.13 | 1.00 | 0.75 | 17.8 | 23.0 | | 2.00 | 1.00 | | 1.40 | 1.40 | Bal. | | | | | | | | | | | 4.5 | INCO |
| M-813 | 0.08 | | | 18.0 | 35.0 | | 4.00 | | | 2.25 | 1.40 | Bal. | | 52.0 | 52.0 | 41.0 | 30.0 | 22.0 | 13.0 | | | | | General Electric |
| Thermenol | | | | | 48.0 | | 1.70 | | | | 16.00 | Bal. | 0.3V | 18.5 | 9.4 | | | | | | | 3.5 | 5.0 | Allew-Knox |
| NA-22H (C) | 0.50 | 1.30 | 1.00 | 21.0 | | | | 0.00 | | | | Bal. | | | | | | | | | | | | |
| **GROUP II—CHROMIUM NICKEL COBALT & IRON ALLOYS** | | | | | | | | | | | | | | | | | | | | | | | | |
| N-155 | 0.12 | 1.50 | 0.50 | 21.0 | 20.0 | 20.0 | 3.00 | 2.00 | 1.00 | | | Bal. | 0.15N | | 38.0 | 23.0 | 19.5 | 12.0 | | | | | | Union Carbide |
| N-154 | 0.32 | 1.50 | 0.50 | 21.0 | 20.0 | 21.0 | 3.00 | 2.00 | 1.00 | | | Bal. | | 50.0 | 40.0 | 31.0 | 20.0 | 15.0 | | | | 2.5 | | Union Carbide |
| N-155, HS-95 | 0.15 | 1.50 | 0.50 | 21.0 | 20.0 | 20.0 | 3.00 | 2.50 | 1.00 | | | Bal. | | | | | 18.0 | 13.0 | 12.0 | 8.0 | | | | Union Carbide |
| HS-96 | 0.33 | 1.50 | 0.50 | 17.0 | 26.0 | 24.0 | 3.00 | 2.00 | | | | Bal. | 0.15N | | | | | | | | | | | Haynes Stellite |
| N-150 | 0.42 | 1.00 | 0.61 | 14.0 | 19.5 | 19.0 | 3.00 | 4.00 | | | | Bal. | | 45.0 | 33.5 | 28.5 | 23.0 | 18.0 | 14.5 | 12.0 | 9.6 | | | Union Carbide |
| S-497 | 0.40 | 1.50 | 0.70 | 20.0 | 20.0 | 20.0 | 4.00 | 4.00 | | | | 24.0 | | 48.0 | 38.0 | 40.0 | 20.0 | 20.0 | 16.0 | 12.5 | 9.0 | 5.0 | | Allegheny Ludlum |
| S-816 | 0.38 | 1.50 | 0.70 | 20.0 | 20.0 | 43.0 | 4.00 | 4.00 | 4.00 | | | 3.0 | | 66.0 | 50.0 | 40.0 | 30.0 | 26.0 | 18.0 | 15.5 | 9.0 | 5.5 | | Allegheny Ludlum |
| S-844 | 0.30 | | | 25.0 | 20.0 | 46.0 | 4.00 | 4.00 | 2.00 | | | 1.0 | | | | | | | | | | | | Allegheny Ludlum |
| V-36 | 0.31 | 0.90 | 0.50 | 25.0 | 20.0 | 42.0 | 4.00 | 2.00 | 2.00 | | | 3.0 | | | | | | | | | | | | Allegheny Ludlum |
| K-42-B | 0.05 | 0.70 | 0.70 | 18.0 | 43.0 | 22.0 | | | | 2.5 | 0.2 | 13.0 | | 66.0 | 40.0 | 35.0 | 23.0 | 18.0 | 15.0 | 11.0 | | | | Westinghouse |
| Refractaloy 26 | 0.05 | 0.70 | 0.70 | 18.0 | 37.0 | 20.0 | 3.00 | | | 2.6 | 0.2 | 18.0 | | 80.0 | 63.0 | 37.0 | 27.0 | 17.5 | 11.0 | | | | | Westinghouse |
| Refractaloy 70 | 0.03 | 2.00 | 0.30 | 20.0 | 20.0 | 30.0 | 8.00 | 4.00 | | | | 15.0 | | 56.0 | 42.0 | 51.0 | 38.0 | 27.0 | 18.0 | 12.0 | 10.0 | | | Westinghouse |
| Refractaloy 80 | 0.10 | 0.60 | 0.70 | 20.0 | 20.0 | 30.0 | 10.00 | 5.00 | | | | 14.0 | | | | 33.0 | 24.0 | 19.0 | 15.0 | | | | | Westinghouse |

Note -- (C) = cast
[a] For rupture in 100 and 1000 hr. Not for design purposes.
[b] Maximum.

Table 5 Superalloys (Cont'd)

| Alloy | C | Mn | Si | Cr | Fe | Co | Mo | W | Ti | Al | B/other | Ni | ... | ... | ... | ... | ... | ... | ... | Producer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Haynes No. 93 | 0.10 | 1.50 | 0.50 | 21.0 | 18.0 | 12.0 | 4.0 | | | | 0.035 | 50.0 | 33.0 | | 15.0 | | | | | Haynes Stellite |
| Timken X | 0.13 | 1.44 | 0.75 | 18.8 | 28.6 | 30.7 | 10.5 | | | | 0.10B | | | | 17.0 | | | | | Timken |
| Ticonium | 0.01 | 0.80 | 0.21 | 23.0 | 33.0 | 31.0 | 6.0 | | | | | | | | | | | | | |
| M-203 | 0.07 | | | 19.5 | 24.5 | 36.5 | | | 1.50 | 0.75 | 0.22B | 52.5 | 33.0 | 22.0 | 5.7 | 16.0 | 18.8 | | 1.6 | General Electric |
| M-204 | 0.07 | | | 18.5 | 24.5 | 40.5 | | | 1.20 | | 0.22B | 84.0 | 59.0 | 54.5 | 29.5 | 40.0 | 17.5 | | | General Electric |
| M-205 | 0.07 | | | 17.0 | 24.5 | 37.5 | | | 1.50 | | | 83.0 | 67.5 | 53.0 | 28.5 | 38.7 | 16.8 | | | General Electric |
| 2DN | 0.17 | | | 15.0 | 42.5 | 41.0 | | | 1.25 | | 3.0V | 79.0 | 64.0 | 50.5 | 27.0 | 36.8 | 11.2 | | | General Electric |
| 23 N. + V | 0.20 | | | 15.0 | 30.0 | 37.0 | 4.6 | | | 4.10 | | 52.0 | 42.5 | 34.5 | 19.0 | 26.0 | | 15.0 | | General Electric |
| Jetalloy 1570 | 0.35 | | | 20.0 | 25.0 | 30.0 | 6.5 | | | | Bal. | | | | | 47.0 | 25.0 | | | |
| U-912 | Var. | | | 20.0 | 25.0 | 35.0 | 8.0 | | | | | | | | | | | | | |
| CMCN | | | | | | | | | | | | | | | | | | | | |

GROUP III—NICKEL-BASE ALLOYS

| Inconel | 0.04 | 0.35 | 0.20 | 15.0 | 7.0 | | | | | | | 22.0 | 14.5 | 10.5 | 0.8 | | | | 2.5 | INCO |
| Inconel M | 0.03 | | | 16.0 | 11.5 | | | | 3.00 | 0.60 | | | | | | | | | | |
| Inco 540 | 0.04 | 0.60 | 0.25 | 15.0 | 15.0 | | | | 2.50 | 0.60 | 7.0 | 74.0 | 54.0 | 43.0 | 30.0 | 15.0 | 11.5 | 7.5 | 3.2 | INCO |
| Inconel W | 0.04 | 0.70 | 0.30 | 13.0 | 13.0 | | 0.90 | | 2.50 | 0.90 | 7.0 | 80.0 | 68.0 | 50.0 | 40.0 | 28.0 | 18.0 | 18.0 | 3.3 | INCO |
| Inconel X | | | | | | | 0.90 | | | | | | | | | | | | 2.3 | INCO |
| Type 550 | 0.04 | | | 13.0 | 13.0 | | 0.90 | 2.40 | 0.90 | 7.0 | | 70.0 | 75.0 | 64.0 | | 34.0 | 21.0 | 18.0 | 10.2 | 3.3 | INCO |
| Inco 700 | 0.10 | 2.00 | 0.40 | 15.0 | Bal. | 3.0 | | | 2.25 | 3.00 | 4.0 | | | | 42.0 | 25.0 | 28.0 | 16.0 | 6.0 | INCO |
| Inco 702 | 0.10 | 2.00 | 1.00 | 15.0 | Bal. | | | | 2.25 | 3.00 | 4.0 | | | | | | | | | INCO |
| Inco 706 | 0.10 | 2.00 | 1.00 | 15.0 | Bal. | 40.0 | | | 2.75 | 3.50 | 4.0 | | | | | | 23.0 | | | INCO |
| Inco 707 | 0.10 | 2.00 | 1.00 | 11.0 | Bal. | 3.0 | | | 2.75 | 3.50 | 4.0 | | | | | | | | | INCO |
| Inco 70B | 0.10 | 2.00 | 1.00 | 11.0 | Bal. | 3.0 | | | 2.75 | 3.50 | 4.0 | | | | | | | 29.0 | | INCO |
| Inco 702 | 0.10 | 2.00 | 1.00 | 7.5 | 13.0 | 3.0 | | | 3.00 | 3.75 | 4.0 | | | | | | | | | INCO |
| Inco 740 | 0.10 | 2.00 | 1.00 | 7.5 | 7.0 | 3.0 | | | 3.00 | 3.75 | 4.0 | | | | | 20.0 | 19.0 | 11.0 | 5.3 | INCO |
| Inco 71 | 0.10 | 2.00 | 1.00 | 15.5 | 15.5 | 3.0 | | | 1.70 | 2.70 | 0.5 | | | | | 8.8 | | | | INCO |
| Inco 73? | 0.07 | 2.00 | 0.70 | 55.0 | | 20.0 | | | | | 20.0 | 51.0 | 40.5 | 35.0 | 34.0 | 12.7 | | | | Haynes Stellite |
| Hastelloy A | 0.10 | 0.80 | 0.70 | | 62.0 | 28.0 | | | | | 5.0 | 47.5 | 42.5 | 32.0 | 18.5 | 14.5 | 13.2 | 9.2 | | Haynes Stellite |
| Hastelloy B (C) | 0.10 | | 0.70 | 1.0 | 57.0 | 17.0 | | | | | 5.0 | | | | 19.0 | | | | | Haynes Stellite |
| Hastelloy C (C) | 0.10 | | 10.00 | 10.0 | 85.0 | | 4.0 | | | | 1.0 | | | | | | | | | Haynes Stellite |
| Hastelloy R-235 | | | | 15.5 | Bal. | 2.5 | | 2.5 | 2.00 | 10.0 | 4.0Cu | 40.0 | | 40.0 | 30.0 | 30.0 | 24.0 | 18.0 | | Haynes Stellite |
| Hastelloy N | 0.12 | 1.0 | | 2.5 | Bal. | 24.5 | | | | 5.5 | 0.5V | 44.5 | 30.5 | 25.0 | 18.5 | 10.0 | | | | Haynes Stellite |
| Hastelloy X | 0.15 | | | 22.5 | 42.0 | 7.0 | | | | Bal. | | | | 57.5 | 31.5 | 20.0 | 19.5 | | | Haynes Stellite |
| Waspaloy | 0.07 | | | 19.0 | 28.0 | 14.0 | | | 2.5 | 1.20 | 2.0 | | | | 41.0 | 30.0 | | | | Pratt & Whitney |
| Udimet 500 | 0.12 | 1.25 | 2.50 | 20.0 | Bal. | 10.0 | 4.0 | | 3.0 | 2.75 | 2.0 | | 62.0 | 47.0 | 55.0 | 29.0 | 25.0 | 18.0 | 11.0 | Utica Drop Forge |
| GMR-235 (C) | 0.15 | 5.00 | 5.00 | 20.0 | Bal. | | | | 2.0 | 3.00 | 10.0 | | | | | | | | | General Nuclear |
| Nimcastic (C) | 2.00 | | | 23.0 | Bal. | | | | | | | | 52.0 | 35.0 | 25.0 | 18.0 | 16.0 | 10.0 | | Pratt & Whitney |
| M-252 | 0.00 | | | 20.0 | 34.0 | 4.0 | | | 2.5 | 0.75 | 2.0 | | | | 47.0 | 29.0 | 28.0 | | | General Electric |
| GE-B-12 (C) | 0.08 | 0.40 | | 20.0 | 62.0 | 10.0 | | 2.00 | 2.3 | 1.10 | 4.0 | | | 52.0 | 28.0 | 17.0 | | | | General Electric |
| M-900 | 0.10 | | | 22.5 | 22.5 | | | | | | 13.0 | | | 70.0 | 40.5 | 2.3 | 26.0 | | | General Electric |
| I-136U (C) | | | | 10.0 | 10.0 | 22.0 | | 2.00 | | | 4.5 | | | | | | | 10.5 | 9.4 | General Electric |
| Nimalloy | | 5.00 | | 22.0 | 58.0 | 0.0 | | | | | 0.0 | | | | | | | | 4.8 | INCO |
| Illium G | | | 0.11 | 22.0 | 64.0 | | | 8.00 | | | 2.0Cu | | | | | | | | | Illium Corp. |
| Illium R | | | | | | | | | | | | | | | | | | | | Illium Corp. |

GROUP IV—COBALT ALLOYS

| HS-21, Vitallium | 0.25 | 0.60 | 0.80 | 27.0 | 3.0 | 62.0 | 5.0 | | | | 1.0 | 51.0 | 44.2 | 32.0 | 22.0 | 14.2 | 16.7 | 13.2 | 9.4 | 7.0 Haynes Stellite |
| HS-23, 61 (C) | 0.33 | 0.50 | 0.80 | 24.0 | 2.0 | 66.0 | | 0.6 | | | 1.0 | 58.0 | 47.0 | 33.0 | 27.0 | 21.8 | 12.0 | 12.0 | 8.6 | 5.4 |
| HS-25, L605 | 0.12 | 1.50 | 1.00 | 20.0 | 10.0 | 24.0 | | 15.0 | | | 1.0 | 70.0 | 58.0 | 43.0 | 23.0 | 17.0 | 15.5 | 10.5 | 7.0 | 3.8 Haynes Stellite |
| HS-27, L605 (C) | 0.50 | 1.00 | 1.00 | 32.0 | 34.0 | 34.0 | 8.0 | | | | 1.0 | 40.0 | 40.0 | 36.5 | 23.4 | 18.4 | 12.0 | 6.8 |
| HS-30, W22-19 (C) | 0.50 | 0.50 | 1.00 | 26.0 | 16.0 | 51.0 | 0.0 | | | | 1.0 | 55.0 | 47.0 | 47.0 | 28.0 | 36.0 | 21.7 | 15.8 | 14.8 | 10.0 7.1 |

## Table 5 Superalloys (Cont'd)

| Alloy | Nominal Chemical Composition per cent | | | | | | | | | | | | | Characteristic Rupture Strengths,[a] 1000 psi | | | | | | | | | | Probable Patentee |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | Cr | Ni | Co | Mo | W | Cb | Ti | Al | Fe | Other | 1200 F 100 | 1000 | 1350 F 100 | 1000 | 1500 F 100 | 1000 | 1600 F 100 | 1000 | 1800 F 100 | 1000 | |
| GROUP IV -- COBALT-BASE - ALLOYS - Continued | | | | | | | | | | | | | | | | | | | | | | | | |
| HE-31, X-40 (C) | 0.40 | 0.80 | 0.80 | 25.0 | 10.0 | 55.0 | - | 8.0 | - | - | - | 1.0 | - | 56.0 | 45.0 | 44.0 | 33.0 | 23.4 | 23.4 | 21.0 | 17.0 | 7.4 | 7.0 | Haynes Stellite |
| HE-36, L251 (C) | 0.40 | 1.20 | 0.30 | 19.0 | 10.0 | 36.0 | - | 14.5 | - | - | - | 1.0 | 0.03B | - | - | 48.0 | 41.5 | 25.5 | 25.5 | 23.0 | 18.5 | 10.5 | 7.2 | |
| X-50 (C) | 0.76 | 0.60 | 0.50 | 22.5 | 20.0 | 40.0 | - | 12.0 | - | - | - | 2.5 | - | - | - | - | - | 29.5 | 22.0 | - | - | 10.0 | 7.7 | |
| X-63 (C) | 0.40 | - | - | 23.0 | 10.0 | 58.0 | 6.0 | - | - | - | - | 1.0 | - | 54.0 | 45.5 | 38.0 | 30.1 | 24.3 | 17.7 | - | - | 8.0 | - | General Electric |
| VF-31 | 0.15 | 1.42 | 0.42 | 20.3 | 9.9 | Bal. | 2.6 | 10.7 | - | 1.0 | - | 4.0 | - | - | - | - | - | 23.0 | 18.0 | - | - | - | - | Crucible Steel |
| I-336 | 0.29 | - | - | 19.2 | 13.5 | 50.0 | - | 12.0 | 0.90 | - | - | 1.3 | - | 80.0 | 62.5 | 48.0 | 34.6 | 23.8 | 17.0 | - | - | - | - | |
| HE-1049 (C) | 0.40 | 0.80 | 0.80 | 20.0 | 10.0 | Bal. | - | 15.0 | - | - | - | 3.06 | 0.40B | - | - | - | - | 45.0 | 35.0 | - | - | - | - | Haynes Stellite |
| CF-63 (C) | 0.50 | - | - | 23.0 | 10.0 | 55.0 | - | 7.5 | - | - | - | 1.5 | - | - | - | - | - | - | - | - | - | - | - | |
| GROUP V -- FOREIGN ALLOYS British Alloys | | | | | | | | | | | | | | | | | | | | | | | | |
| Rex 78 | 0.01 | 0.80 | 0.70 | 14.0 | 18.0 | - | 4.0 | - | - | 0.6 | - | Bal. | 4.0Cu | 34.7 | - | - | - | - | - | - | - | - | - | Brown Firth |
| 32b | 0.25 | 3.00 | - | 17.0 | 17.0 | 7.0 | 2.5 | - | 1.80 | - | - | Bal. | - | 40.3 | - | 25.1 | - | - | - | - | - | - | - | Brown Firth |
| 337 | 0.20 | - | - | 17.0 | 17.0 | 7.0 | 3.0 | - | - | 0.8 | - | Bal. | 3.0Cu | - | - | - | - | - | - | - | - | - | - | Brown Firth |
| Rex 32b0 | 0.63 | 0.90 | 1.25 | 14.3 | 14.6 | 9.5 | 2.0 | 2.2 | 2.80 | - | - | Bal. | - | - | - | - | - | - | - | - | - | - | - | Brown Firth |
| Rex 400 | 0.09 | 0.12 | 0.62 | 19.2 | 76.0 | - | - | - | - | 2.1 | 0.6 | Bal. | - | - | - | - | - | - | - | - | - | - | - | Brown Firth |
| Rex 467 | 0.20 | - | - | 14.0 | 10.0 | - | 2.0 | - | 1.00 | 0.8 | - | Bal. | 2.5Cu | 40.0 | 40.0 | 25.0 | 25.0 | - | - | - | - | - | - | Brown Firth |
| F.C.B. (T) | 0.12 | - | - | 17.5 | 12.0 | - | - | 3.0 | - | - | - | Bal. | - | 19.0 | 19.0 | - | - | - | - | - | - | - | - | Brown Firth |
| H.R. Crown Max | 0.23 | 0.65 | 1.16 | 23.2 | 12.3 | - | - | - | 1.70 | - | - | Bal. | - | 31.5 | 19.2 | 19.2 | - | - | - | - | - | - | - | Wm. Jessops |
| R-20 | 0.15 | 0.80 | 0.30 | 13.0 | 14.0 | - | - | 2.5 | - | - | - | Bal. | - | - | - | - | - | - | - | - | - | - | - | Wm. Jessops |
| R-22 | 0.25 | 1.00 | 1.00 | 23.0 | 14.0 | - | - | 2.3 | 0.90 | - | - | Bal. | - | - | - | 19.0 | 11.9 | 6.3 | 6.3 | - | 3.6 | - | - | Wm. Jessops |
| G-21 | 0.40 | 0.70 | 1.40 | 13.0 | 13.0 | 10.0 | 2.6 | 2.3 | 3.00 | - | - | Bal. | - | 48.2 | 35.8 | 25.0 | 18.8 | 14.3 | 13.0 | 10.3 | 8.1 | - | - | Wm. Jessops |
| G-18B | 0.40 | 0.80 | 1.00 | 13.0 | 13.0 | 10.0 | 1.8 | 2.3 | 3.00 | - | - | - | - | - | - | 26.4 | 19.9 | 16.2 | 11.2 | 11.0 | 7.2 | - | - | Wm. Jessops |
| G-19 | 0.40 | 0.80 | 1.00 | 19.0 | 13.0 | 10.0 | - | - | - | - | - | Bal. | - | - | - | - | - | - | - | - | - | - | - | Wm. Jessops |
| G-32 | 0.27 | 0.80 | 0.50 | 19.0 | 10.5 | 46.0 | 2.2 | 2.2 | 1.40 | - | - | Bal. | 3.0V | - | - | 44.0 | 35.8 | 28.7 | 20.8 | 18.8 | 13.2 | 6.7 | - | Wm. Jessops |
| G-34 (C) G-35 (C) | | | | Casting alloy similar to G-32 / Austenitic nickel-base casting alloy | | | | | | | | | | 38.0 | 29.1 | 24.0 | 18.2 | 15.9 | 12.2 | 11.7 | 8.8 | 6.6 | 4.6 | Wm. Jessops |
| G-42 | 0.25 | 1.80 | 1.00 | 19.0 | 15.0 | 25.0 | 2.7 | 3.5 | 2.90 | 1.2 | - | Bal. | - | - | - | 50.4 | 38.0 | 28.0 | - | - | - | - | - | |
| Multi-Alloy | 0.08 | 0.70 | 0.80 | 20.5 | 40.5 | 3.3 | - | - | - | 1.5 | - | Bal. | - | 46.1 | - | - | - | - | - | - | - | - | - | United Steel |
| Red Fox 33 | 0.12 | 0.60 | 0.80 | 20.0 | 30.0 | - | - | - | - | 0.4 | - | 2.4 | - | - | - | - | - | - | - | - | - | - | - | Samuel Fox |
| Nimonic 75 | 0.03 | 0.70 | 0.50 | 20.0 | 76.0 | - | - | - | - | 0.4 | 0.06 | 0.5 | - | 62.7 | - | 39.0 | 25.8 | 17.2 | 7.7 | - | - | - | - | Mond Nickel |
| Nimonic 80 | 0.05 | 0.70 | 0.56 | 20.0 | 76.0 | - | - | - | - | 2.3 | 1.00 | 0.5 | - | 67.3 | 50.5 | 46.4 | 31.0 | 21.5 | 9.8 | - | - | - | - | Mond Nickel |
| Nimonic 80A | 0.06 | 0.50 | 0.60 | 20.0 | 76.0 | - | - | - | - | 2.3 | 1.00 | 0.5 | - | 76.1 | 56.0 | 50.6 | 38.0 | 26.0 | 17.9 | - | - | - | - | Mond Nickel |
| Nimonic 90 | 0.08 | 0.50 | 0.40 | 20.0 | 58.0 | 16.0 | - | - | - | 2.3 | 1.40 | 0.5 | - | - | 63.0 | 55.5 | - | 33.0 | - | - | - | - | - | Mond Nickel |
| Nimonic 95 | 0.08 | 0.50 | 0.40 | 20.0 | 58.0 | 16.0 | - | - | - | 2.5 | 1.60 | 0.5 | - | - | - | - | - | - | - | 21.1 | - | - | - | Mond Nickel |

Note -- Cb + Ta contents are shown under Cb.

Table 5 Superalloys (Cont'd)

**German Alloys**

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WF 1000 | 0.38 | 0.52 | 1.84 | 14.8 | 12.9 | - | Bal. | 0.23 | 2.5 | 0.15 | - | - | 50.0 | 34.0 | 24.0 | 15.0 | Krupp |
| Tinidur | 0.04 | 1.00 | 0.73 | 14.7 | 26.1 | - | Bal. | - | - | - | - | 2 2b | 0.15 | 0.13N | | | |
| (a) | 0.10 | - | 1.00 | 17.0 | 15.0 | - | Bal. | 2.00 | - | 1.30 | - | - | - | - | | | |
| (b) | - | 0.50 | - | 18.0 | 10.0 | - | Bal. | - | 0.5 | - | 0.40 | - | - | | | |
| (c) | 0.10 | 18.00 | 0.50 | 18.0 | - | - | Bal. | - | 1.0 | - | - | - | | | |
| (d) | 0.10 | - | 0.70 | 12.0 | 9.0 | - | Bal. | - | - | - | - | - | | | |
| (e) | - | - | - | 18.0 | 10.0 | - | Bal. | - | - | - | 0.60 | - | 0.7V 0.2N | | | |
| (f) | 0.10 | 0.90 | 0.60 | 18.0 | 8.0 | - | Bal. | - | 1.00 | - | 1.00 | - | 1.0V | | | |

**Russian Alloys[c]**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| EI-72 | 0.25/0.35 | <0.6 | 2/3.0 | 11.5/14 | 6.5/7.5 | - | Bal. | - | - |
| EI-211 | <0.20 | 0.7/1.2 | 2/3.0 | 18/20 | 13/15 | - | Bal. | - | - |
| EI-332 | <0.25 | 2.0 | <1.0 | 24/27 | 19/22 | - | Bal. | - | - |
| EIa-38 | 0.30/0.40 | 2.0 | 2/3.0 | 16/20 | 23/27 | - | Bal. | - | - |
| EI-69 | 0.40/0.50 | <0.7 | 0.3/0.8 | 13/15 | 13/15 | - | Bal. | - | - |
| EI-240 | 0.40/0.50 | <0.7 | 2.7/3.3 | 13/15 | 13/15 | - | Bal. | 0.25/0.40 | 2.0/2.8 |
| EI-203 | 0.35/0.45 | 3/5 | 1.4/1.8 | 13/15 | - | - | Bal. | <0.5 | 2.0/2.8 |
| EI-310 | 0.35/0.45 | 4/6 | 1.0/1.6 | 17/20 | 3.0/7.0 | - | Bal. | - | 2.0/2.8 |
| EI-312 | 0.35/0.45 | 3/5 | 1.4/2.2 | 17/20 | 5.0/7.0 | - | Bal | - | 0.8/1.0 |

[c] From Iron Age, March 19, 1953, p.138.
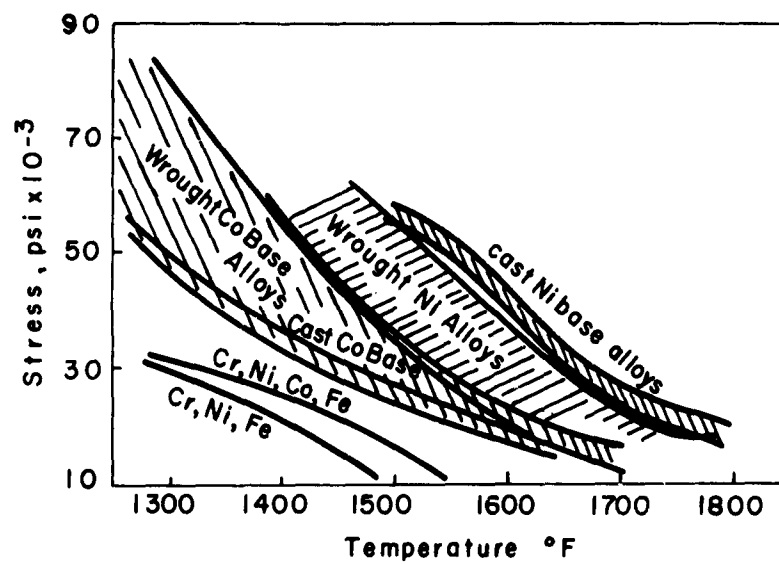
Fig. 33    Stress-Rupture in 100 Hours.

figures. The materials are annealed Stellite 25, heat treated Inconel X, compared with full-hard 301 stainless steel, annealed A110-AT titanium alloy and alclad 2024-Ts aluminum alloy.

Figure 35 shows the effect of temperature after a 1C second heating time and two different holding times on the 0.2% offset yield strength of test materials at a strain rate of 1.0 in/in/sec. 301 stainless exhibits excellent strength to 900°F but drops sharply - flattening out at 1600°F. Inconel X holds well to 1200°F and drops rather rapidly - about 1150°F. Stellite 25 and Inconel X exhibit superior yield strength above 1600°F. Alclad 2024-T3 loses its strength quite rapidly after 450°F.

Figure 34 shows the effect of temperature, after a 10 second heating time and two different holding times, on the ultimate tensile strength of test metals at a strain rate of 1.0 in/in/sec. 301 stainless exhibits maximum ultimate tensile strength at 900°F and is superior to Inconel X to approximate 1100°F. Inconel X leads the groups to approximately 1700°F with Stellite 25 exhibiting the highest properties to the highest test temperature.

The periods during which space vehicles will be subjected to extremely high temperatures will be very short. There are available considerable very short time creep-rupture data on aluminum, titanium, and steel alloys. Space vehicle and drag chute studies will require similar data on superalloys, such as creep-rupture data for 10-1800 seconds. Conversely, a need also exists for extremely long-time mechanical properties of the superalloys.

The available alloys in this field have been in a continuing process of evolution. At the present time several new alloys have indicated potential properties for rather high stresses to temperatures as high as 1800°F. There are numerous factors which must be taken into consideration in considering the use of these alloys for space vehicles. Space applications apparently will require a large use of heat resistant alloys in the form of thin sheet, tubular products, wires, etc. Relatively few of the alloys have been produced and used in this form. However, procedures have been developed for producing and fabricating Inconel X, L605, etc, in sheet form. Optimum properties for sheet materials of this type are shown in Figure 36.

The general history of the superalloys shows a close correlation between alloy and fabrication developments. Thus, many alloys are now commonly melted, hot worked and rolled to sheet which a few years

Figure 35. Super Alloy Yield Strength

10 sec Heating
Strain Rate 1·0 in/in /sec



Figure 34. Ultimate Tensile
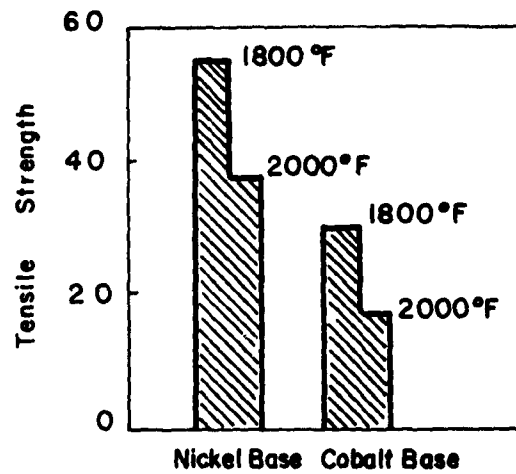
Figure 36    High temperature sheet
            alloys.

1- Titanium MST        5- 17-17 PH        9 - Alumiunium
2- Udimet  700         6- M 252 Or        10-Cast Nickel
3- Inconel  X          7- L605            11- 321 Stainless
4-Molybdenum
        6 Al- 4V       8- Udimet 600
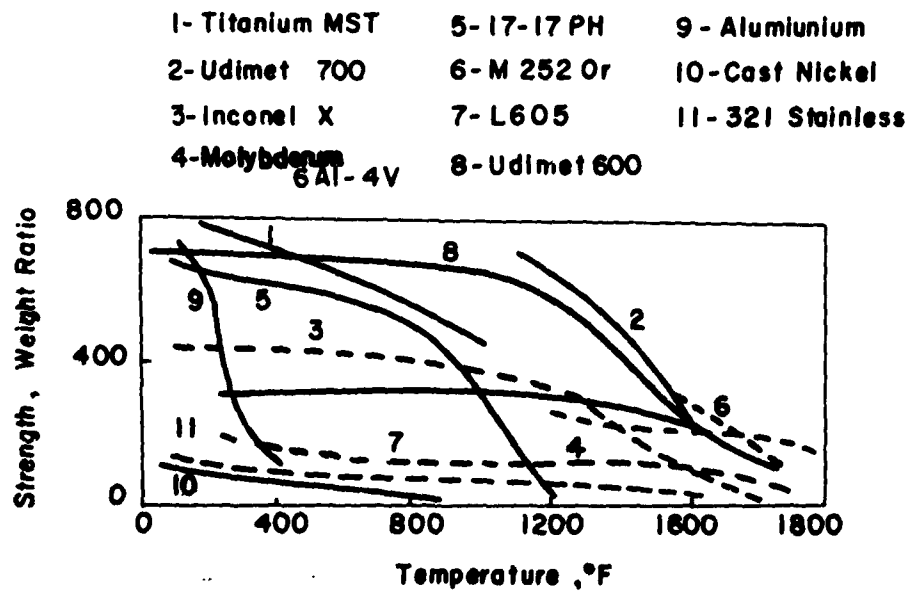


Figure 37    Strength to weight ratio.

ago were impractical to even make into forgings. Tremendous strides have been made in the technology of producing such alloys. Presumably, therefore, some of the alloys which will withstand the higher temperatures under high stresses will eventually be produced as sheet. Thus, the properties of such alloys are an indication of what may be available in the future, but it is doubtful that they will be useful much over 2000°F.

Those alloys which now show the highest strengths at temperatures of 1700-1800°F are now only available as investment castings. They do not appear promising as sheet or wire material.

On the basis of a strength to weight ratio comparison of the high temperature capabilities of existing alloys, it may be quite readily seen in Figure 37 that superalloys are superior on a strength to weight ratio up to 1800°F. It is quite possible that refractory alloys will be available for limited applications with a superior strength to weight ratio at temperatures in excess of 2000°F. However, fabricability and oxidation resistance continue to be a problem in the role of refractory alloys with little assurance of success at this time.

It is generally considered that the superalloys are reaching the limit of their increase in temperature while retaining present levels of load carrying ability. This is due to the service temperatures approaching the melting points of the alloys based on Cr-Ni and/or Co. Based on the experience of the last few years it seems that the most that can be expected is an increase of metal service temperature of 100° to 200°F. These last increases in temperature apparently will come slowly and will be difficult from the production and fabrication viewpoint.

Oxidation and corrosion are becoming an increasing problem as these temperatures are raised. Heretofore, the superalloys have in general had adequate corrosion resistance from the alloying elements commonly used to develop properties. This also is reaching an end point and surface protection may be necessary for the high strength alloys at the higher temperatures.

The technology of producing superalloys has undergone large improvements during the last 10 to 15 years. Vacuum and consumable electrode melting have resulted in materials which are much easier to produce and fabricate. The role of trace elements in properties and quality has been recognized. The growing understanding of the metallurgy of the alloys in terms of the minor elements should lead to pronounced advantages in the future.

For example, the role of extremely small percentages of boron and zirconium in increasing the rupture life of nickel base alloys is quite vividly illustrated in Figure 38. Elongation is plotted against time. The tests were conducted at 1600°F and 25,000 psi on experimental nickel base heats. By melting in an aluminum crucible with boron and zirconium held to a minimum, a 60 hour creep life was obtained as against over a 600 hour creep life when the same alloy was melted in a zirconia crucible with additions of boron and zirconium (.0088% B - .01% Zr).

The effect of titanium on the 1500°F, 35,000 psi rupture life of Waspaloy is illustrated in Figure 39. The variation of the percentages of titanium from .6 to 1.6 (1%) increased the rupture life from 38 hours to approximately 170 hours.

Encouraging increases in the high temperatures properties of superalloys by careful control of trace elements has been demonstrated and it is reasonable to assume that continuing improvement in properties will be attained through further studies of trace element behavior in superalloys.

Dispersion hardening is a principal method of attaining added strength in existing superalloys. In order to strengthen the lattices of superalloys, we must introduce barriers to impede the movement of dislocations. One of the most effective methods is to introduce a hard high strength second phase properly dispersed in the matrix. Such particles pin down dislocations thereby strengthening the alloy.

Superalloys are subject to variation in properties for a number of reasons. The role of trace elements derived from contamination and 'deoxidation" practice is now recognized and when properly developed should lead to improvement in both properties and their uniformity. Over and above this, however, processing conditions can have a pronounced effects on properties. The role of this variable is not very well understood. Certainly, however, proper precautions must be used if and when superalloys are applied to space vehicles to be sure that the unusual conditions of production and fabrication involved do not adversely affect the properties. We cannot overemphasize the importance of this problem and the need for more basic information on the metallurgy involved. The application of superalloys to the new field will require careful technical development to make sure that the alloys will have the expected properties in the finished vehicle.

One important facet in the field of processing variables has
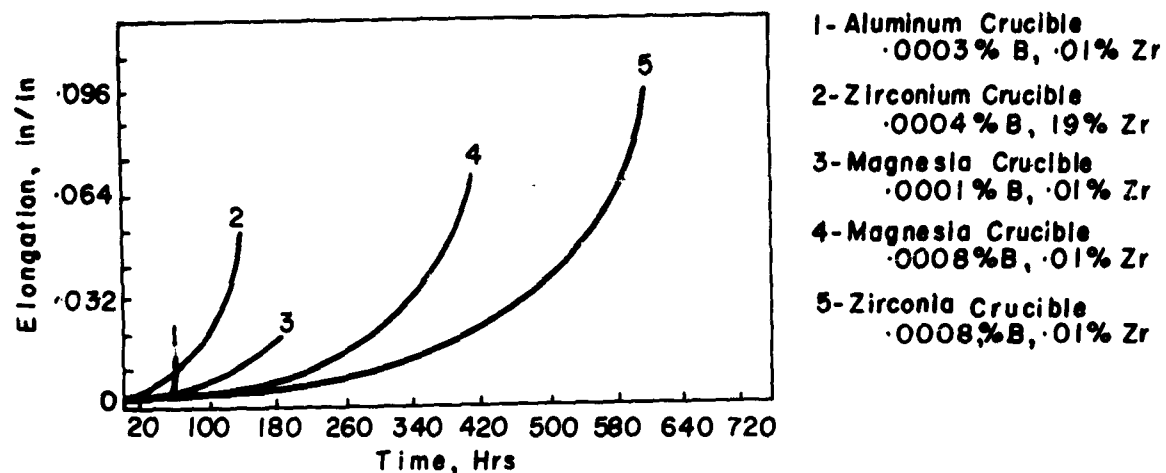
**Figure 38    Effect of boron and Zirconium on creep characteristics.**

Legend:
1- Aluminum Crucible ·0003% B, ·01% Zr
2- Zirconium Crucible ·0004% B, 19% Zr
3- Magnesia Crucible ·0001% B, ·01% Zr
4- Magnesia Crucible ·0008%B, ·01% Zr
5- Zirconia Crucible ·0008,%B, ·01% Zr
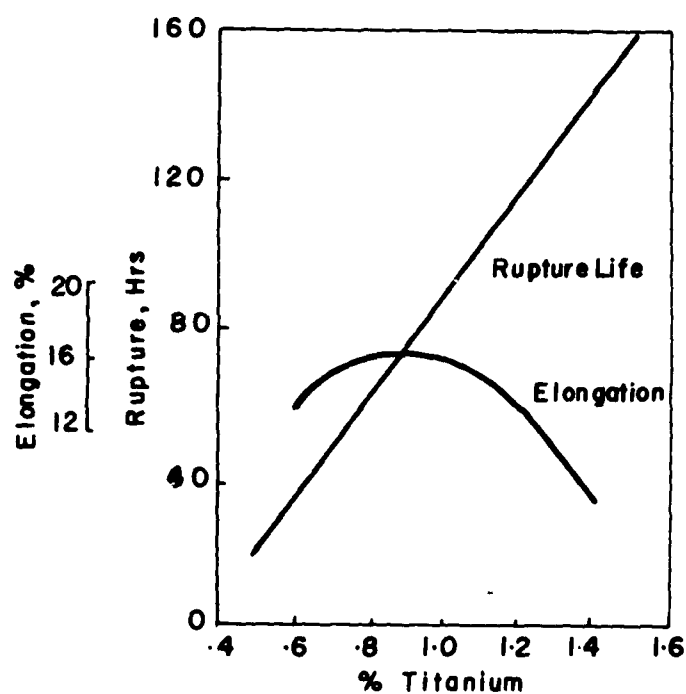


**Figure 39    Waspaloy - Rupture life as a function of % titanium.**

been work aimed at determining the effect of prior working conditions on the properties of a complex, age-hardenable alloy (A-286) when a standard heat treatment is used after the rolling operation.

The rolling temperatures selected for A-286 alloy were room temperature, 1700, 1950, and 2200°F. Reductions were carried out isothermally and on a falling temperature schedule. The high temperature properties were evaluated under various test conditons. Figure 40 shows the results of creep tests at 1200°F and 35,000 psi.

The results speak for themselves. The temperature of rolling has increased the creep strength of A-286 from 300 hours at 80°F to over 1000 hours at rolling temperatures from 1950-2200°F.

Similar studies with favorable results have been conducted on N-155 and 16-25-6 alloys.

A more complete understanding of processing variables is necessary if we are to squeeze the ultimate high temperature strength out of the superalloys. Not only additional prior working data is needed, but also processing data from melting and pouring temperatures to the final finishing process.

One of the most difficult problems associated with the use of superalloys arises from the fabrication problems. Many of the applications require complicated shapes, particularly where cooling is to be used. Not only are the alloys difficult to form for such applications, but they are difficult to weld, braze, and join. In addition such operations can be very detrimental to properties where the welding heat alters the microstructure of the alloys. It seems reasonably sure that if superalloys are to be widely used, there will have to be very extensive developments in the technology of fabricating the finished parts. It can be said with confidence that this area represents the single most critical materials problem in the space vehicle field, whether or not superalloys, refractory metals, or lower alloyed materials are used.

## Elevated-Temperature Data for Particular Superalloys

For service up to 1200°F, data are presented for Hastelloy R 235 and Udimet 500 nickel-base alloys and for N 155 mixed-base alloy. These materials differ from the older nickel-base alloys, such as Inconel-X, in that some of the nickel is replaced with solid-solution hardeners, such as cobalt and molybdenum, and especially in the larger amount of aluminum and titanium precipitation hardeners.
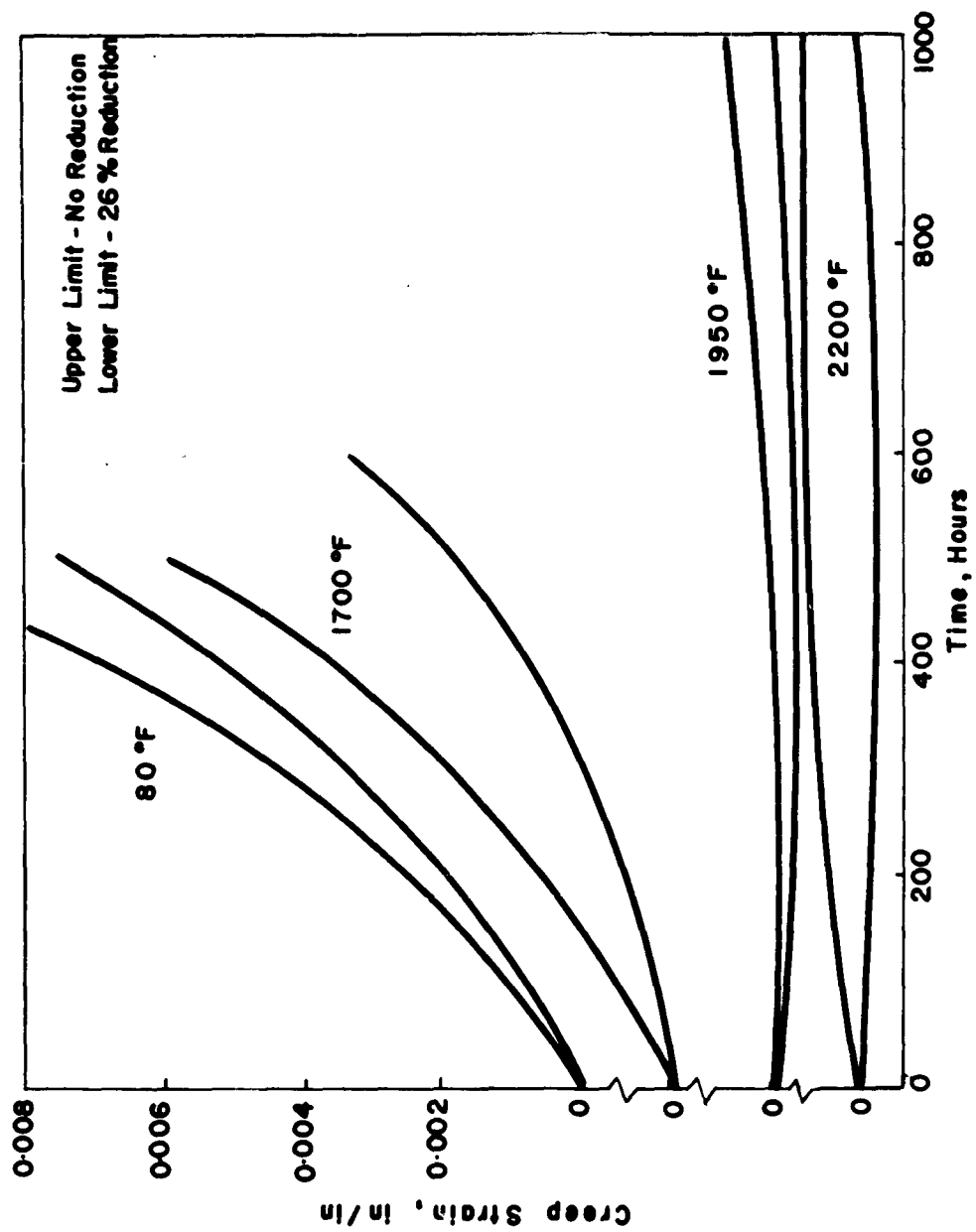
Figure 40  Creep behavior of A-286 as related to prior working.

Tensile property data are presented for Multimet (N 155), Udimet 500 and Hastelloy R 235 (Figures 41 and 42). N 155 is used for comparison because of its past and present extensive use at high temperatures for combustion chambers. All three alloys are being used in sheet-metal applications at service temperatures to 2100°F. The N 155 and Udimet 500 were tested in the mill-annealed condition and the Hastelloy R 235 in the cold-worked and aged condition. For operation below about 1700°F, a considerable increase in strength over the annealed properties can be realized by aging the Udimet 500. At approximately 1200°F, the Udimet 500 shows a considerable increase in yield strength due to the aging of the solution-annealed material. The ability to rapidly heat to the test temperature allows this phenomena to be observed and measured. In a conventional elevated-temperature test, the time normally required for a furnace to heat a specimen would obscure this effect. For the maximum utilization of material for short times, it is desirable to obtain the short-time elevated-temperature strength for the exact time and temperature combination expected in service.

The strength of the Udimet 500 begins to drop off rapidly beyond 1600°F, primarily because of overaging. The cold-worked R 235 also loses strength at 1600°F because the effect of the cold work is disappearing and the material is also overaging. From room temperature to 1800°F, N 155 has a relatively low strength compared to Udimet 500 and cold-worked and aged R-235. Above 1900°F the strength of N-155 compares favorably with the other two alloys. The modulus of elasticity for the three alloys progressively decreases from room temperature to 2200°F. All three materials have a hot-short range with a loss of ductility at 1500 to 1600°F.

Effect of Cold Work on R 235. Dislocation theory predicts that a combination of cold working and subsequent aging of a material will markedly increase its resistance to deformation at elevated temperature. Hastelloy R 235 alloy was cold worked 10% and 20% and subsequently aged at 100°F for 2 hr. Standard elevated-temperature tensile tests by the producer showed significant improvements in strength at 1200°F over material that was aged only. The material was tested on the elevated-temperature testing machine to determine the maximum temperature to which the benefit of cold working and aging could be realized under the the conditions of short-time heating and testing.
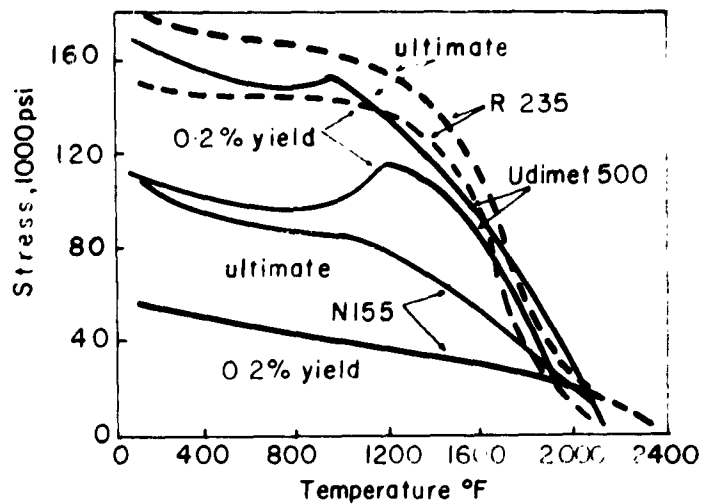
**Fig. 41  Tensile Strength Versus Temperature for High-Elevated-Temperature Alloys**
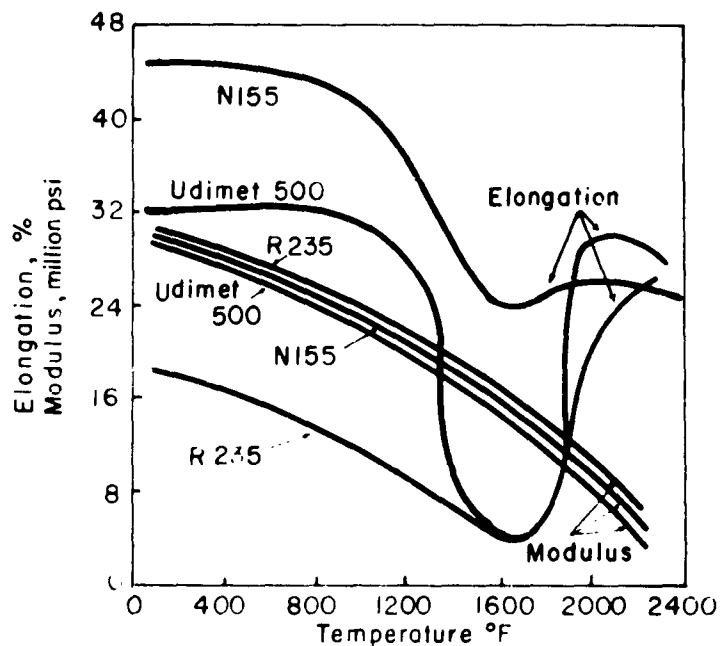


**Fig. 42  Elongation and Modulus of Elasticity Versus Temperature for High-Elevated-Temperature Alloys**

The effect of cold reduction plus aging on the mechanical properties of R 235 is shown in Figure 43. The greater the amount of cold work, the higher are the mechanical properties from room temperature to 1400°F. Above 1400 to 2000°F, the greater the cold work the lower the properties. The yield and tensile strengths are virtually the same at 2000°F for both cold reductions.

Effect of Strain Rate on N-155. As in the case of the magnesium alloys and all other alloys, there is a strain-rate sensitization temperature for N-155 alloy sheet. The ultimate strength is first affected by strain rate at 1200°F and the yield strength at 1400°F (Figure 44). At 1800°F, approximately a ten-fold increase in strain rate raises the yield strength 100%. Increasing the strain rate by a factor of 20 raises the ultimate tensile strength 40% at 1800°F. At 2000°F, the effect of strain rate on the yield strength is more pronounced; at 100-fold increase in strain rate raises the yield strength 180%. The ultimate strength is less affected than the yield strength by strain-rate differences at 2000°F. The strain-rate effect is even more pronounced at still higher temperatures.

Creep Strength of N-155. The ability of the elevated temperature testing machine to measure strain from the instant the load is applied and to hold a constant load makes it possible to plot conventional creep curves and isochronous stress-strain curves for extensions that occur from the first second the load is applied. The short-time creep properties of annealed N-155 are shown in Figure 45. A family of curves showing creep at 2000°F is given for stress levels of 4000, 5000, 6000 and 7000 psi. Note that the short-time creep curves are concave upwards rather than downward as is common for curves obtained from ordinary long-time creep tests. A family of isochronous stress-strain curves for annealed N-155 is shown in Figure 46. These curves illustrate the effect of stress as a function of plastic creep strain for constant times from 1 to 900 sec at 2100°F.

Isochronous stress-strain curves are a recent innovation in presenting test data. For a short-time application, these curves are far easier to analyze and interpret than conventional creep curves. For example, compare Figures 45 and 46 in a hypothetical analysis. Suppose 1% plastic creep strain is the maximum growth that can be tolerated and the missile can be subjected to different trajectories of different times from 30 to 120 sec. From an examination of the isochronous stress-strain curve for the critical
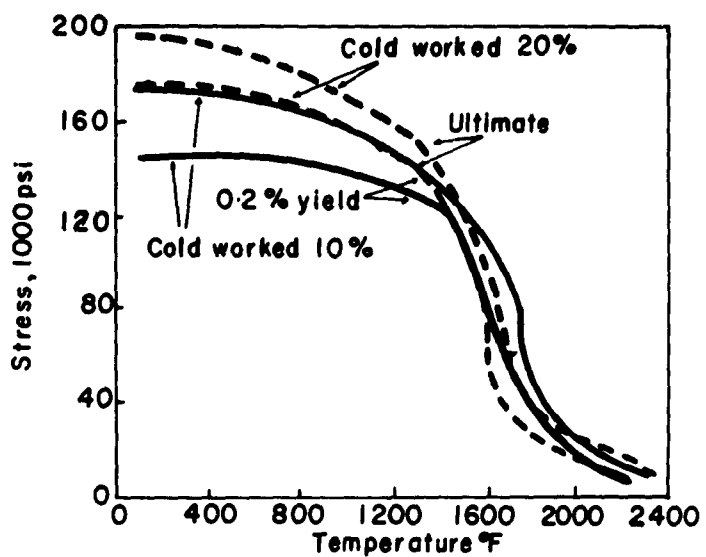
Fig. 43   Effect of Cold Work Prior to Aging
on Tensile Properties of R235
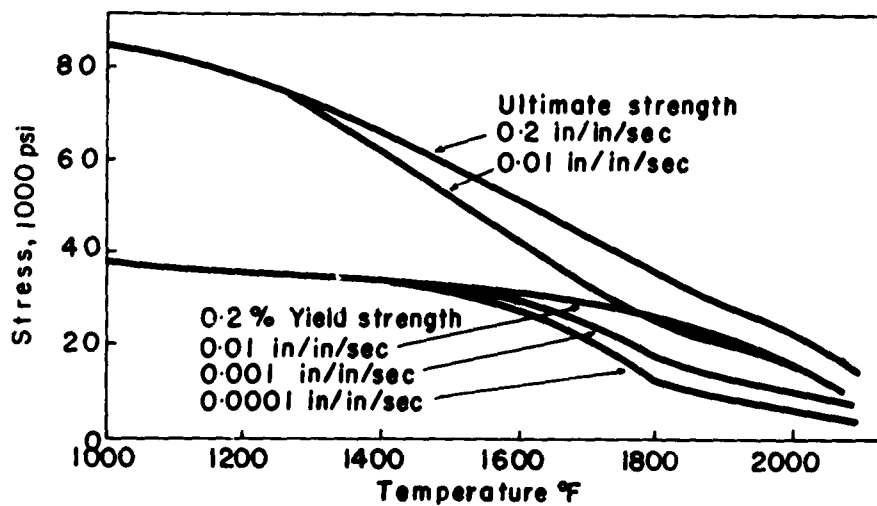


Fig. 44   Effect of Strain Rate on Annealed
Haynes N155
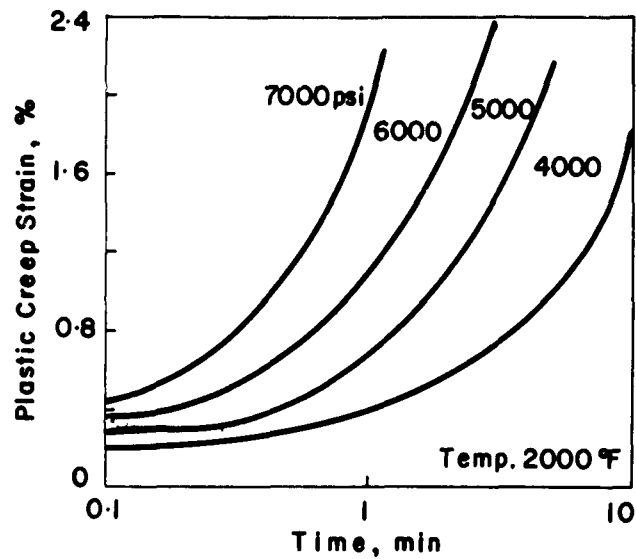
Fig. 45    Short-Time Creep of Annealed
           N155
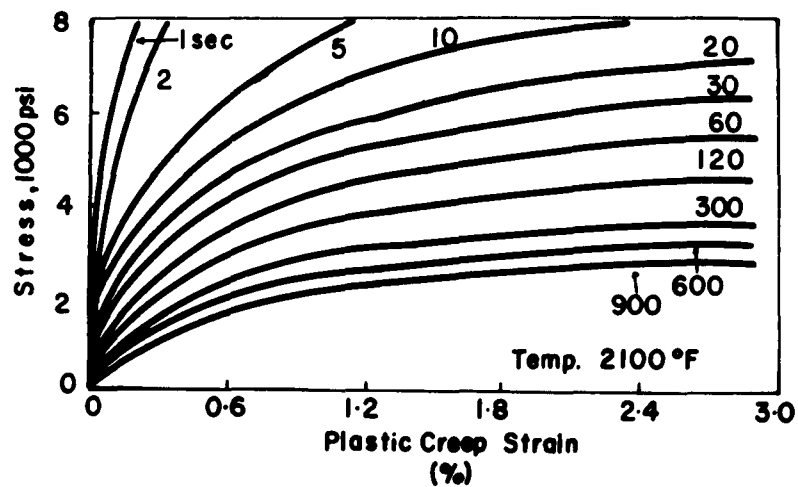


Fig. 46    Isochronous Stress Versus Plastic
           Strain for Haynes Annealed N155 Alloy

plastic creep strain, it is readily seen which stress levels correspond to the missile's trajectories. In conventional creep curves, it is more difficult to determine the required stress levels.

Significance of Short-Time Tests. Missile components for short-time operation at elevated temperatures must have a sensitive balance between tensile and creep properties to accurately determine the limiting material-strength allowables. For example in designing with N 155 to yield stress for the 0.001 in. per in. per sec strain rate, 6,000 psi would result in a sustained load failure in less than 4 min of operation, and 2% creep elongation would occur in 1/2 min. Many missiles are loaded at rates considerably beyond 0.0001 in. per in. per sec. If the yield strength value for the 0.01 in. per in. per sec. strain rate was used for design, failure would occur after considerably less than a minute of sustained load operation. It is this detailed knowledge of the very short-time properties tnat will result in a reliable structure of minimum weight. Lack of such knowledge for short-time service structures will result in either premature failure or excessive weight.

The large reduction in the stress-rupture life of specimens (of the above cited superalloys) exposed to corrosive elements at elevated temperatures has been the subject of investigation. It has been found that at 900°F and below, the stress-corrosion mechanism of failure does not appear to be active, but at 2000°F and above a significant attack of the N 155 takes place at stress levels above 4000 psi.

Promising Alloys Suitable for Wire and Strip

The following sets of curves compare and demonstrate some of the physical properties of a few of the more promising super alloys in wire and strip form.

(a) Tophet "A" is an alloy of 80% nickel and 20% chromium and is essentially iron free. It is recommended for temperatures up to 2100°F (1149°C) and is supplied in bar, rod, wire, ribbon and strip or insulated wire form.

(b) Evanohm is an alloy with a nominal composition of 74.50% Ni, 20% chromium, 2.75% aluminum and 2.75% copper. Evanohm possesses a high tensile strength in fine sizes, a high resistance to corrosion and is non-magnetic. While it was initially developed

for electrical applications, it has excellent mechanical properties.

(c) Cobenium is a heat treatable, high cobalt alloy. It was developed by the Wilbur B. Driver Co. of Newark, New Jersey, following research to develop an alloy that would be as good as or better than spring steel, particularly be highly corrosion resistant. It is completely corrosion resistant to atmospheric conditions and tests have shown that it is more resistant to corrosion than stainless steels. Cobenium generally speaking, has no notch sensitivity and as a spring material has proven to have considerably higher resistance to set and fatigue than carbonspring steel. It will reportedly, at elevated temperatures, retain its elastic properties to a much greater degree and to somewhat higher temperatures than 18/8 stainless steel. Cobenium is a heat treatable alloy readily formed and blanked in the cold work condition. It responds to a simple thermal treatment. The hardening temperatures range from 900° to 1150°F, with time at temperature varying with the temperature used. The nature of the alloy is such that it will not respond to heat treatment from the solution annealed state. It must have some degree of cold work in order to be hardened to higher values than the already high cold worked properties. Naturally a greater amount of cold work within its limit, will produce a correspondingly greater response. For maximum mechanical and spring properties, it has been found that a cold reduction in area of 85% for strip, particularly in the thinner gauges has been most satisfactory. Wire with a cold reduction in area of 48% has proven best.

A. Chemical Composition

| Cobalt | 40% | Manganese | 2% |
| Chromium | 20% | Beryllium | .04% |
| Nickel | 15% | Carbon | .15% |
| Molybdenum | 7% | Iron | Bal. |

B. Mechanical Properties as Heat Treated (Room Temperature)

| Ultimate Strength | 360,000 psi |
| Yield Strength | 280,000 psi |
| Proportional Limit | 233,000 psi |
| Modulus of Elasticity | 29,500,000 psi |
| Shear Modulus (Torsion) | 11,000,000 psi |
| Rockwell Hardness | C-55-60 |

Physical Properties

| Density | .300 lbs/cu.in. |
| Specific Gravity | 8.3 |

Coefficient of Linear Expansion    $12.7 \times 10^{-6}$ Per °C (0-50°C)
Thermoelasticity                   $-39.6 \times 10^{-5}$ Per °C (0-50°C)

Mechanical properties are shown in the following figures 47 to 57.

### Super Alloys - Conclusions

The super alloys represent materials readily usable up to 1900°F, and for short time applications up to 2000°F. However, except for alloys such as Cobenium or Tophet, specifically developed for use in wire-drawn forms, all are rather difficult to form into sheet, strip or wire. The very strengthening mechanisms that cause them to be useful at elevated temperature (solid solution hardening, particle dispersion, etc) cause them to be troublesome to fabricate. For the present they are not attractive for single application to be made of thin sheet or wire.

### NOTE

The material in the introductory section on super alloys is excerpted almost in full from the ARDC Technical Symposium on Materials Research, Development and Application held in Dallas, Texas 9-10 July 1958 -- Talk given by C.B. Hartley.
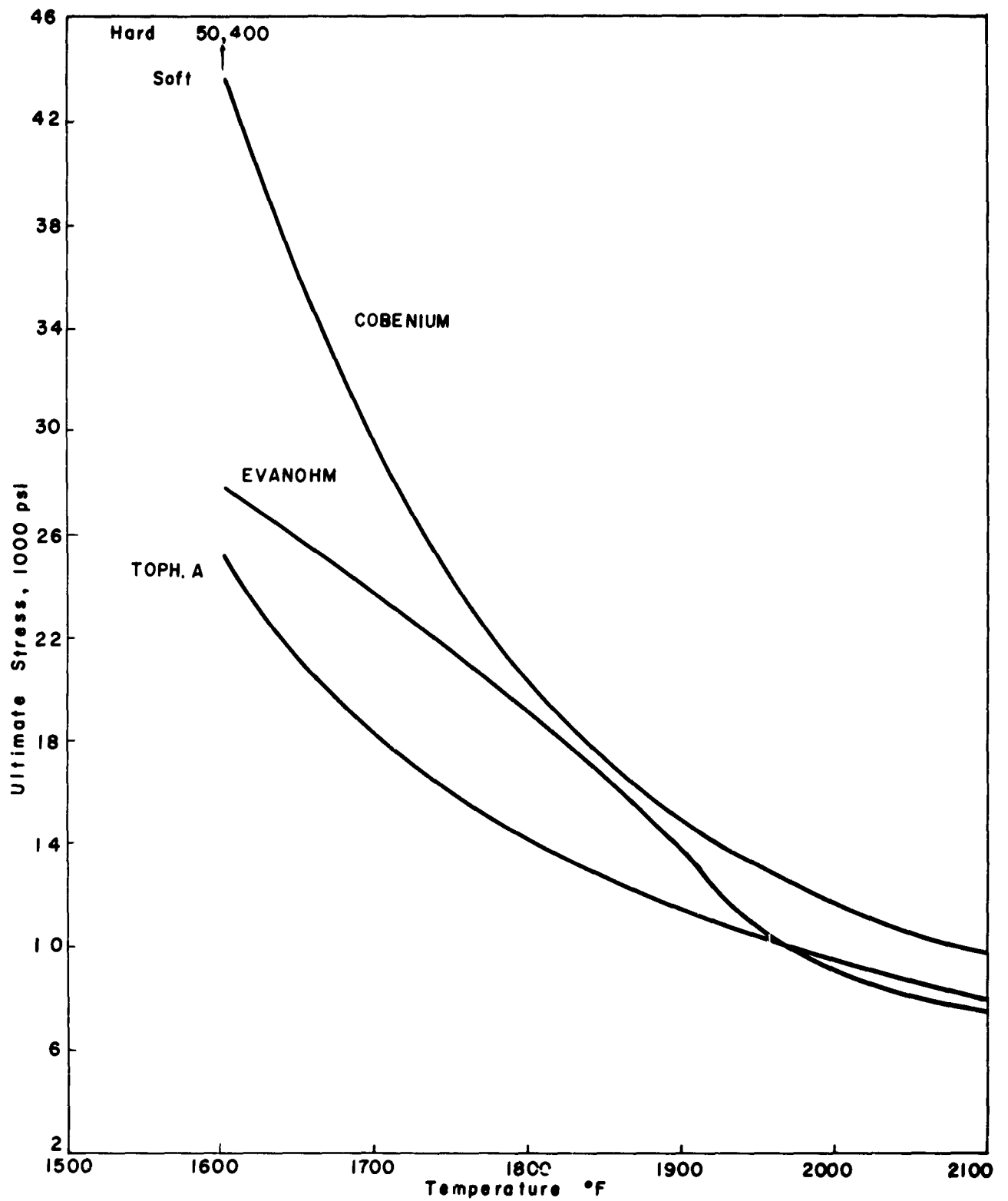
Figure 47. Short Time Elevated Temperature Tensile Test.
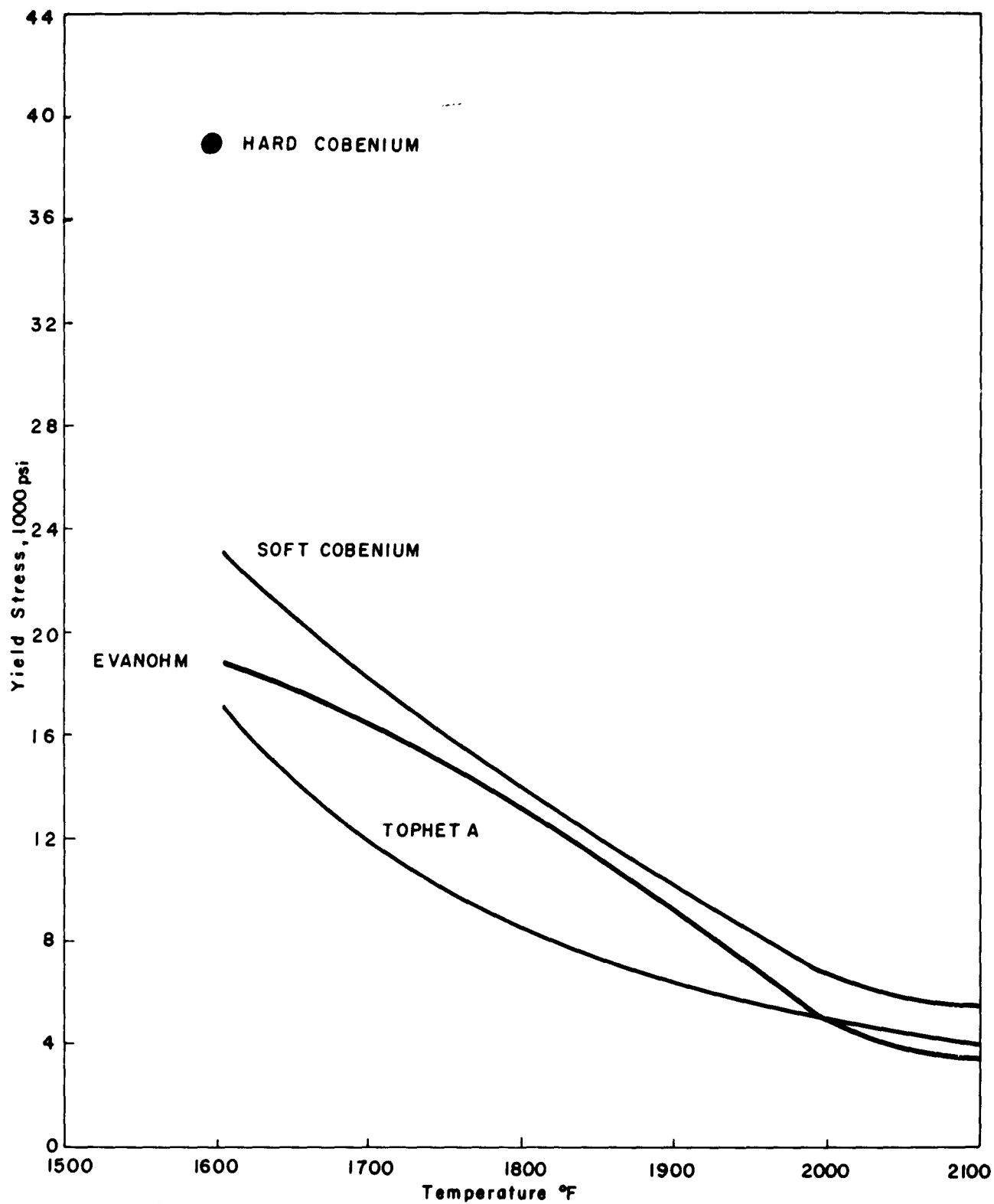
Figure 48. Short Time Elevated Temperature Tensile Test.
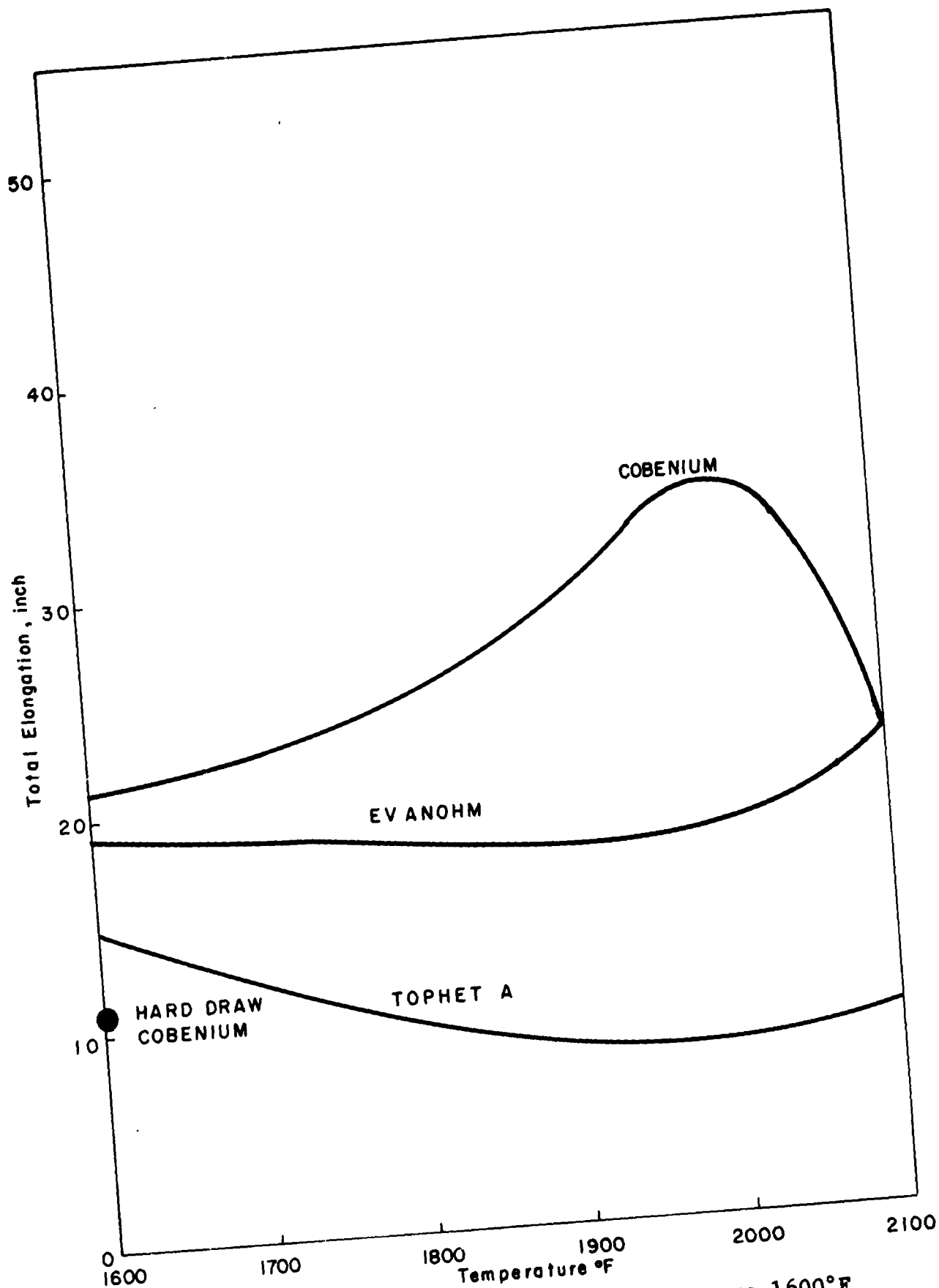
Figure 49. Short Time Elevated Temperature 1600°F Tensile Test.

WADD TR 60-327
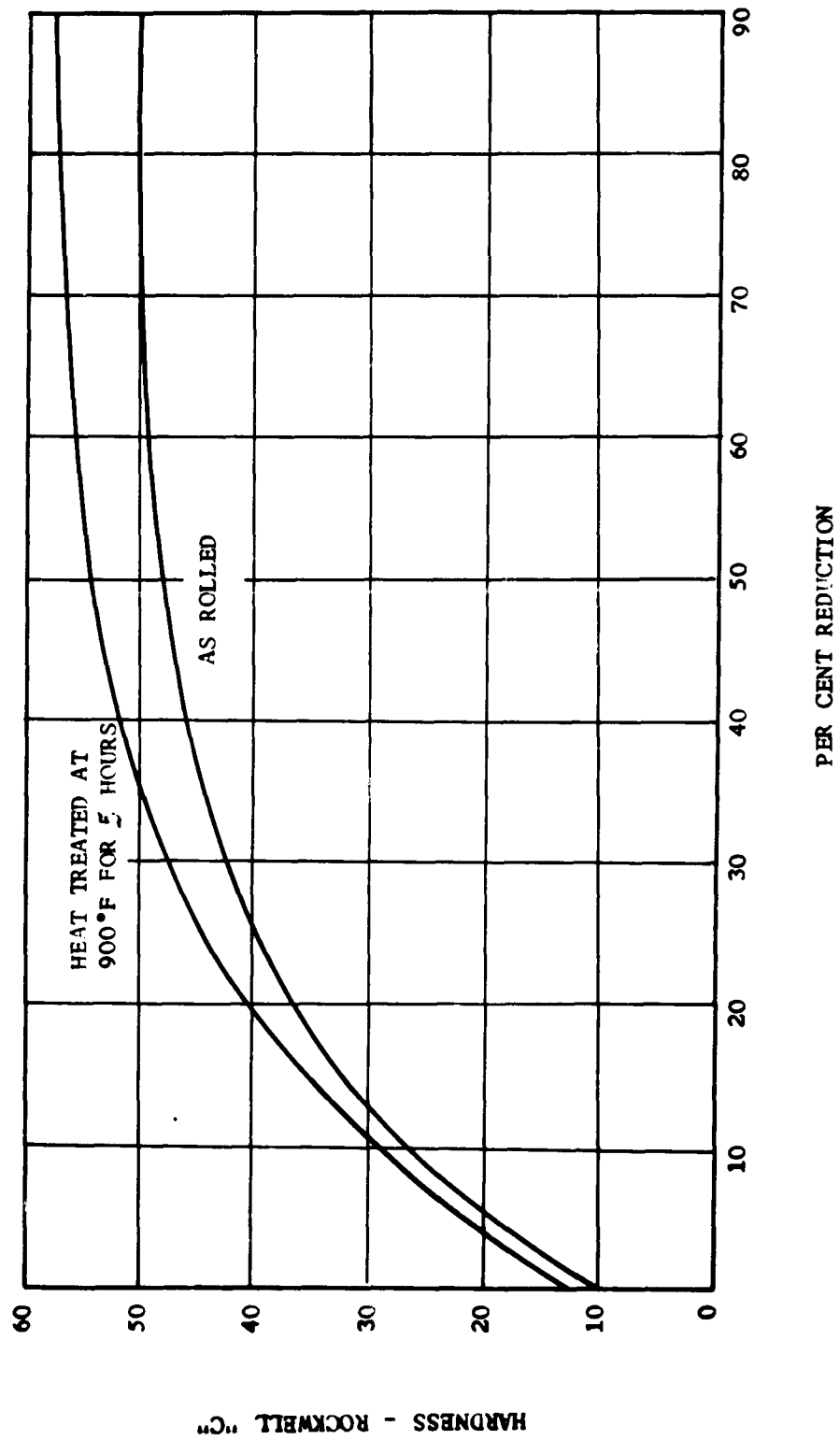
Figure 50  Work Hardening Curve of Cobenium (.20" Strip)

HARDNESS - ROCKWELL "C"

PER CENT REDUCTION
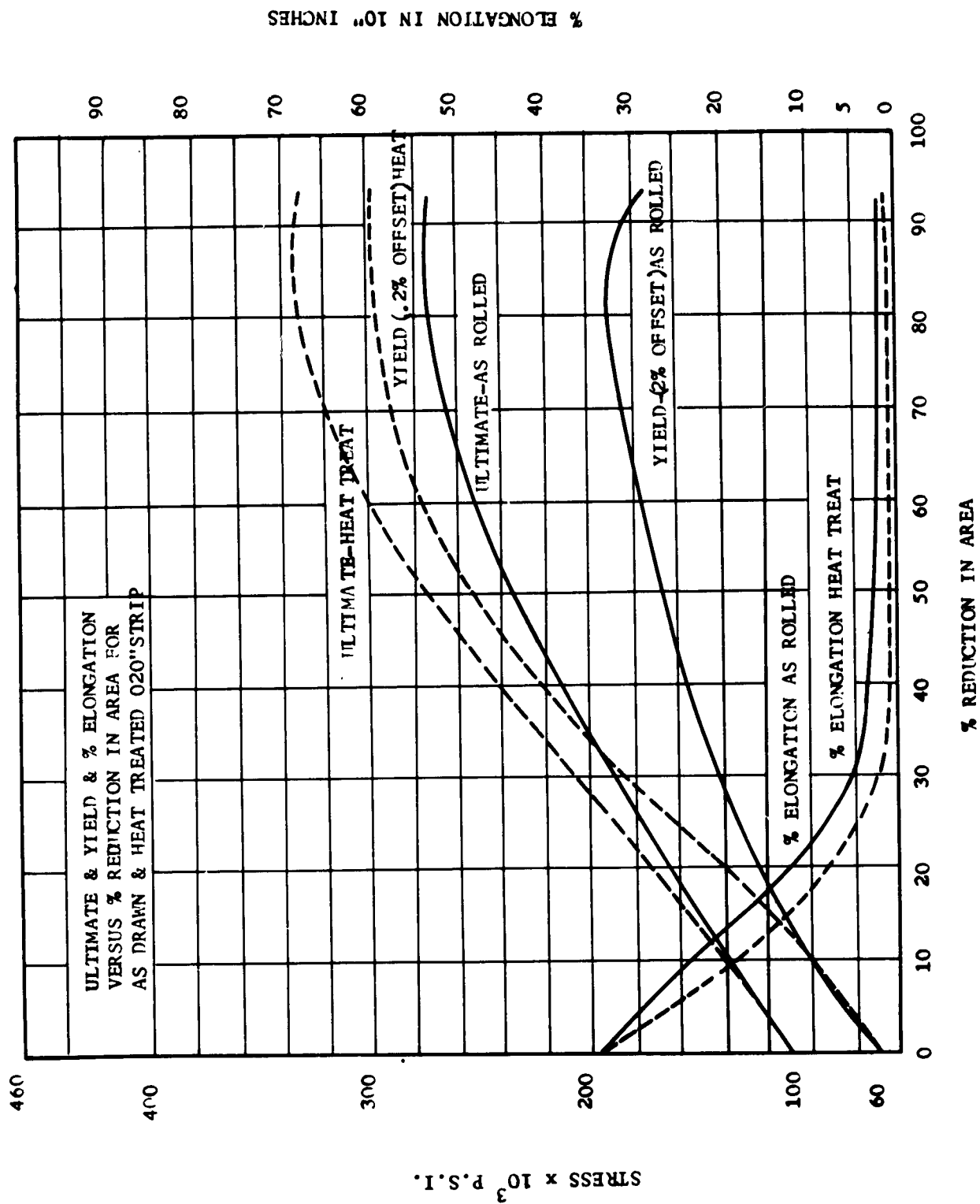
Figure 51 Properties of Cobenium Strip
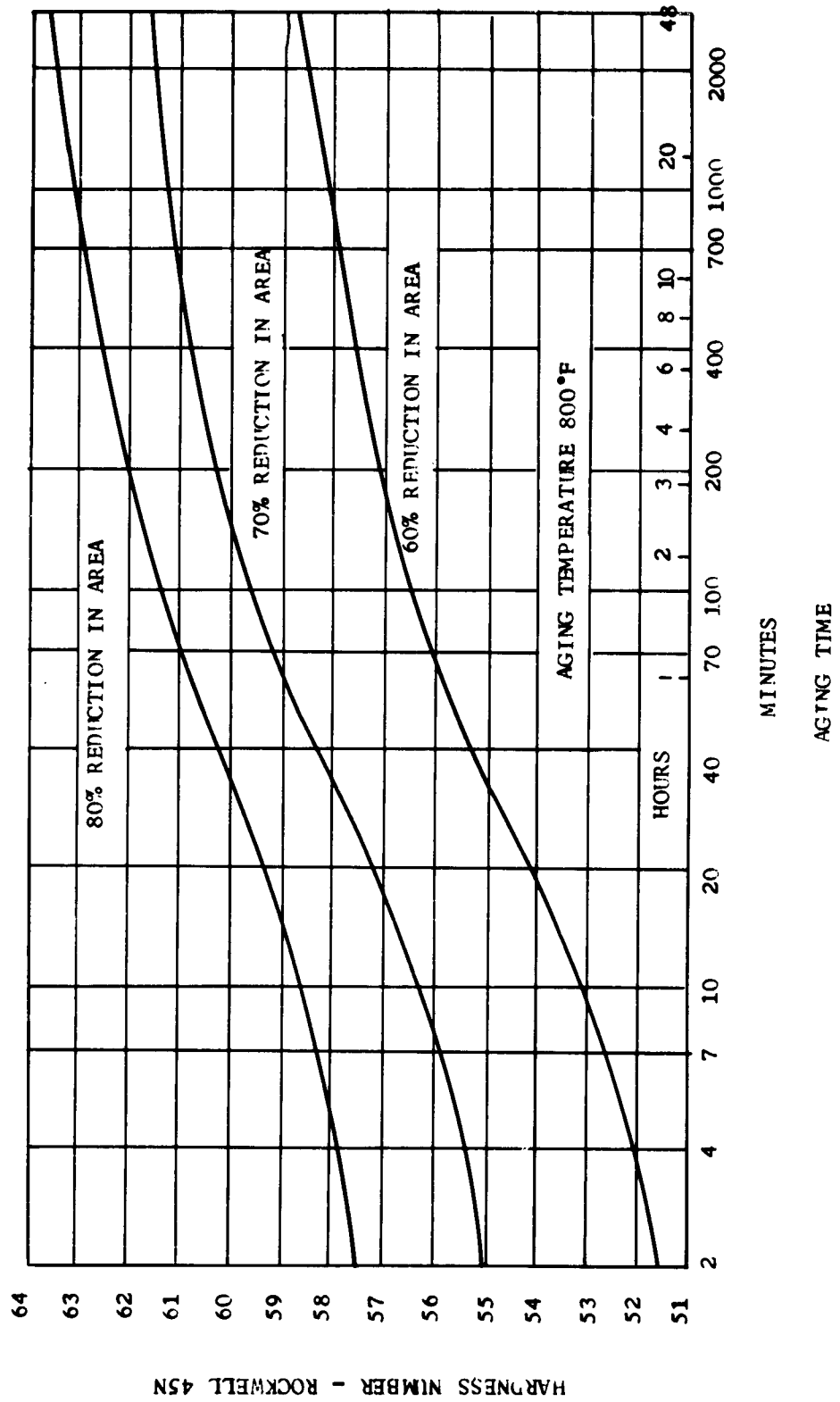
Figure 52  Aging Curves for Cobenium Strip

MINUTES

AGING TIME
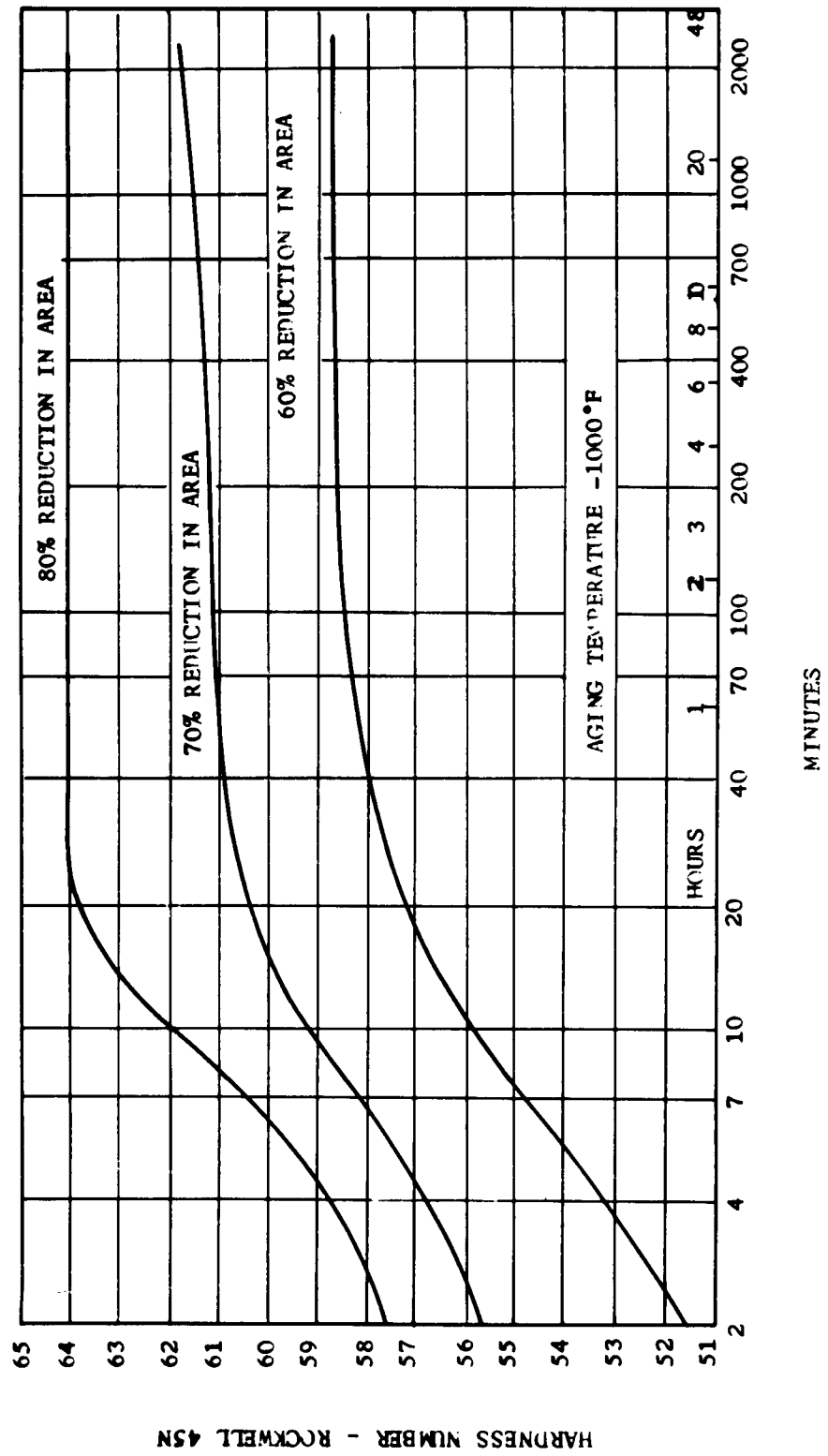
Figure 53  Aging Curves for Cobenium Strip

HARDNESS NUMBER - ROCKWELL 45N
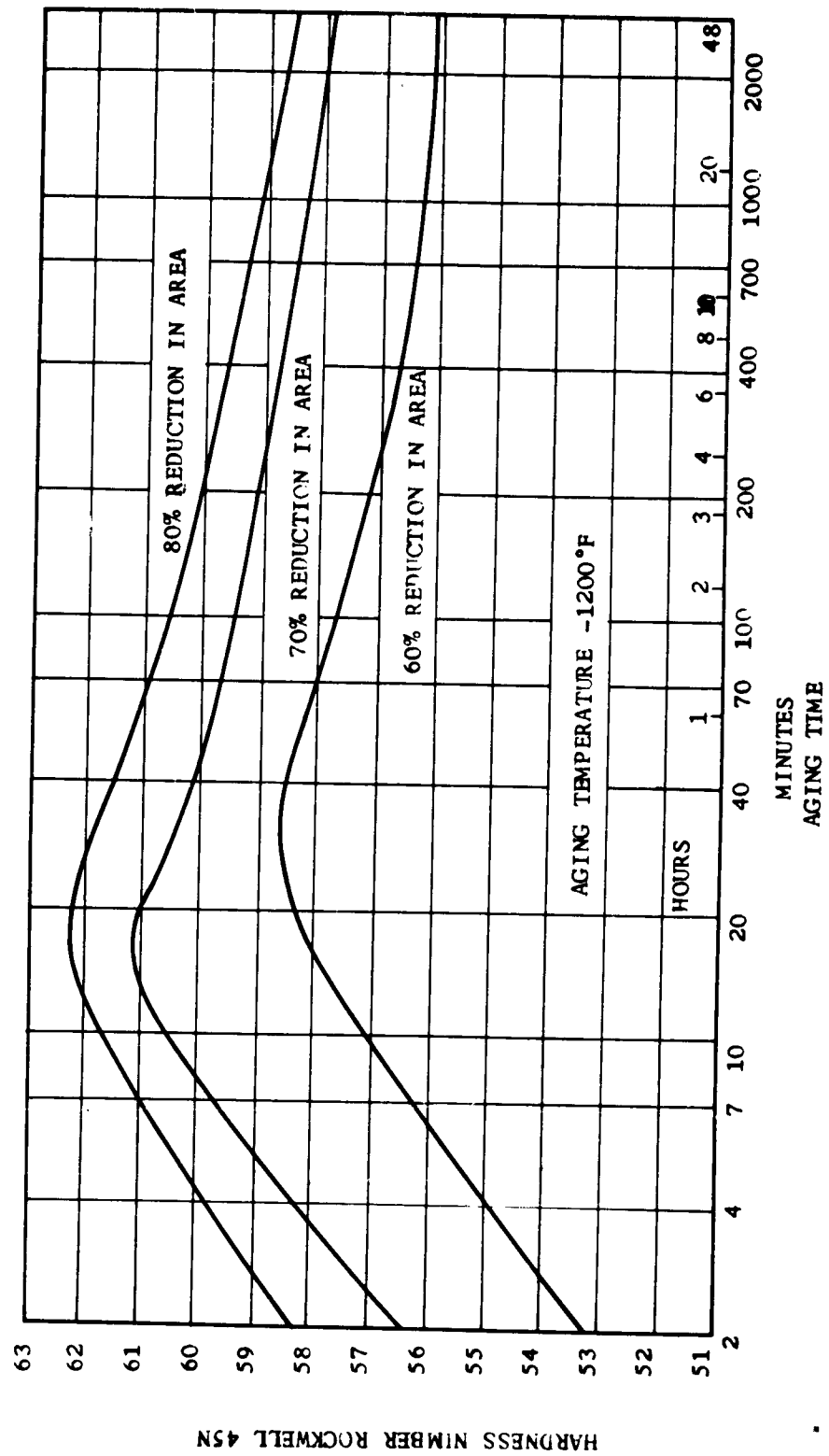
Figure 54 Aging Curves for Cobenium Strip

Figure 55 Average Tensile Properties of Cobenium Wire at
Room and Elevated Temperatures

THE VALUES SHOWN ARE THE AVERAGE OF 5 TEST. ALL
SPECIMENS WERE AGED FOR 5 HOURS AT 900°F & THEN
AGED 100 HRS AT THE TEST TEMP. PRIOR T' TESTING.
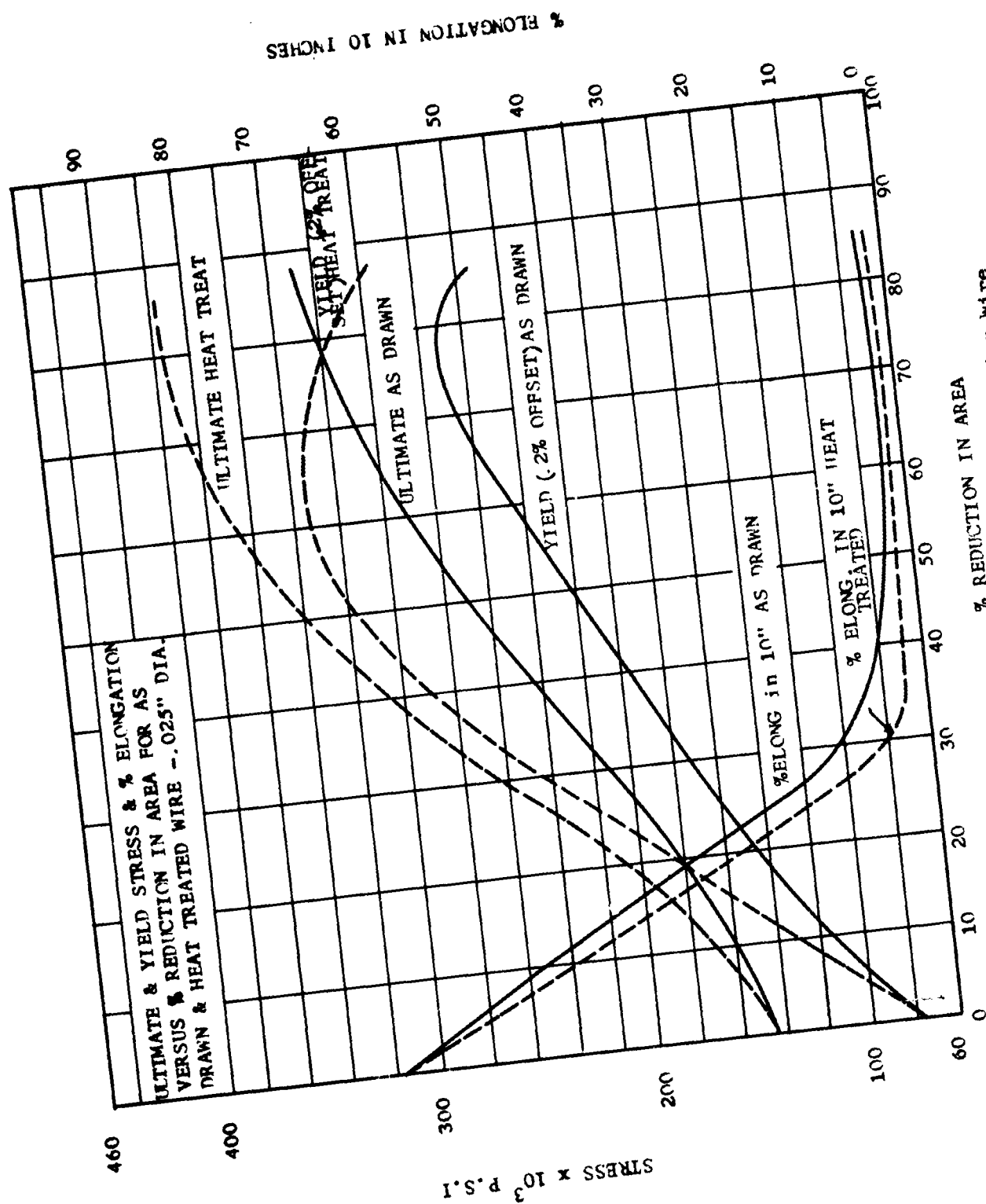
Figure 56   Properties of Cobenium Wire

88

WADD TR 60-327
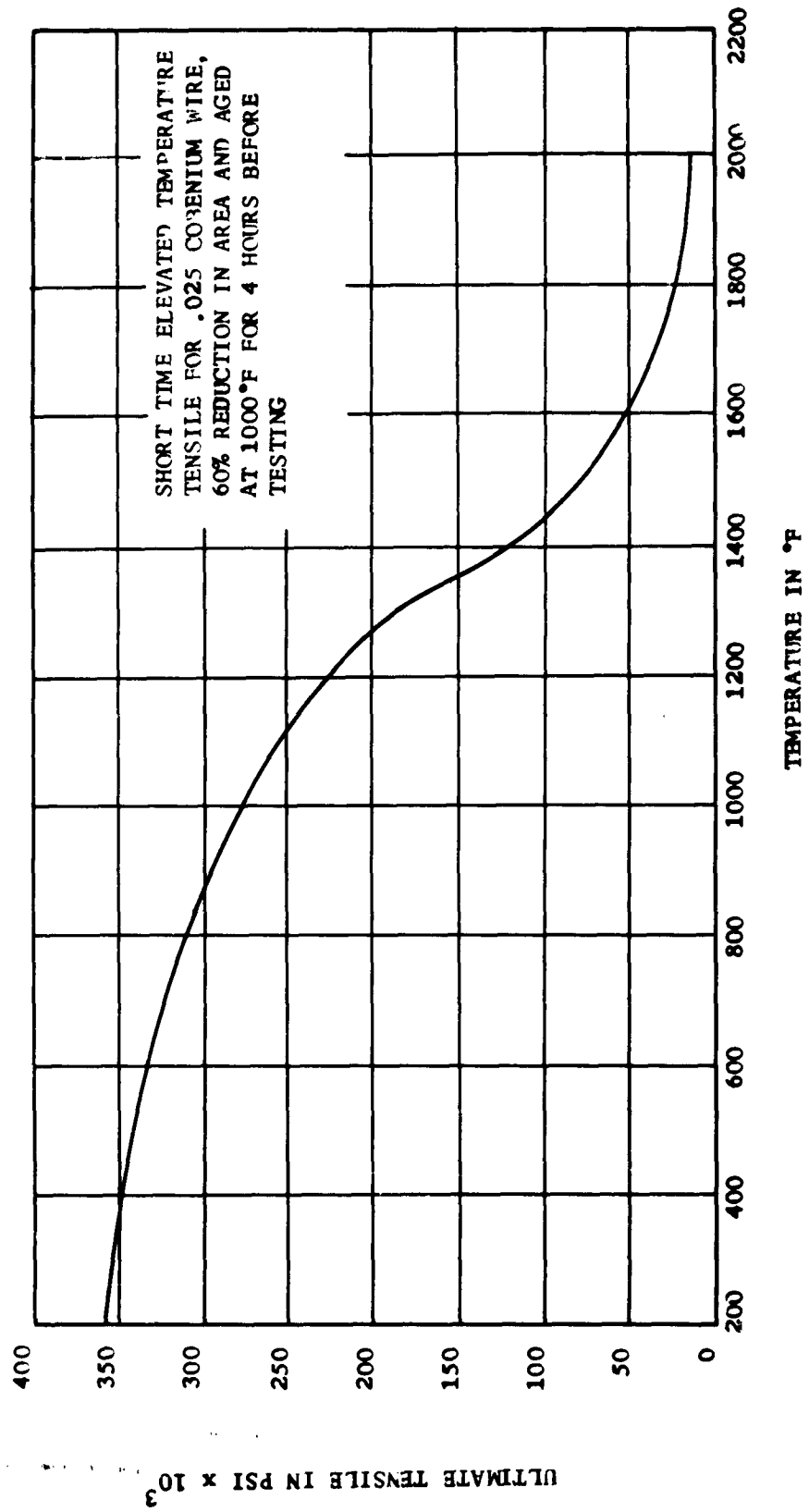
Figure 57 Short Time Elevated Temperature Tensile Tests

SHORT TIME ELEVATED TEMPERATURE
TENSILE FOR .025 COLUMBIUM WIRE,
60% REDUCTION IN AREA AND AGED
AT 1000°F FOR 4 HOURS BEFORE
TESTING

TEMPERATURE IN °F

ULTIMATE TENSILE IN PSI x 10³

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## A.   METALS (Continued)

### 4.   Summary Comparison of High Temperature Metals and Alloys

As can be seen from the reading the previous discussion, many factors enter into the suitability of an alloy or metal for use in parachute drag devices. The material must be formable; it must have good strength to weight ratio; it must be reasonable in cost; it cannot oxidize too rapidly and must be suitable for fabrication into thin sheet or wire. It must not have excessive toxicity.

Among the light metals, aluminum and magnesium alloys have already been eliminated because of their very low range of temperature service, comparatively speaking. Titanium alloys are generally not useable above 1000°F. Beryllium is a very promising metal but, as noted, has many problems related to cost, fabrication, brittleness and toxicity. It will not be available in suitable form for many years. Thus for the range of 1000°F to 1500°F, the light metals may be eliminated.

The super alloys are, in principle, excellent for use in drag devices in the range of 1000°F to 1500°F. In fact, the large majority of super alloys in use today are suitable for temperatures up to 1900°F and perhaps 2000°F. However, all of these alloys have been developed for use in comparatively heavy sections, such as turbine buckets and veins. They are either cast or forged for such applications. In sheet form, many metallurgical problems are encountered in the super alloys, particularly in joining applications. Indeed, the very hardening mechanisms which serve to make super alloys so excellent at elevated temperatures, prevent fabrication at room temperature into sheet and wire. The only super alloys which are exceptions to these statements are those such as Cobenium and Tophet which were developed specifically for electrical wire applications. They can be drawn into very fine wires. Cobenium demonstrates 22,000 psi yield strength and 75,000 psi ultimate strength at 1500°F. The various varieties of stainless steel such as 301 stainless and 316 stainless, both of the 18/8 variety, can also be readily fabricated.

The refractory metals, nickel, molybdenum, cobalt, columbium, tantalum and rhenium have excellent elevated temperature properties when kept in an inert atmosphere or in vacuum. However, all of them readily oxidize in the normal atmosphere at elevated temperature. In fact their oxidation characteristics are so catastrophic, that it would be impossible to use them in fine sections at 1500°F.

Thus, their greatest potential lies in usages where strength is necessary at extreme temperatures and where these metals can be protected from oxidation.

The most effective way of comparing the various refractory metals, super alloys and light alloys of interest, is to plot their mechanical properties on a strength, weight or ratio basis. This has been done in a series of figures following. Most of the data in these figures has been adapted by replotting data to be found in WADC reports: TR57-649 Part 1, TR55-199 Part 2 and Part 3, TR58-440 Part 1. Figure 58 shows that on a strength weight basis for 500 second rupture tests, pure nickel is superior to copper, iron, tantalum and graphite but inferior to molybdenum. At 1500°F, the 500 second rupture strength to weight ratio is approximately 49,000. Figure 59 gives the 10 second rupture strength to weight ratio. The relationship among the metals is the same, and the value for nickel is roughly 65,000. Figure 60 shows the 0.2% offset yield strength to weight ratio for a series of metals up to 1200°F at two different strain rates. In general, 17/7 precipitation hardening stainless steel is as good or better than 41/30 ferritic steel, either heat treated or normalized, or stellite 25 which is a refractory alloy. Figure 61 shows the 0.2% offset yield strength to weight ratio at two different strain rates up to 2800°F for Inconel X and stellite. Inconel X has a yield strength to weight value of approximately 200,000 at 1500°F. Figure 62 is the 0.2% offset yield strength to weight ratio for 301 fully hardened stainless and A110 titanium alloy, as well as an aluminum alloy. For the fully hardened material at the strain rate of 1.0 inches per second at 1500°F, the material is almost as strong as Inconel X at the lowest strain rate. Figures 63 and 64 give similar information for ferritic alloys, titanium and a precipitation hardening stainless steel AM350 up to 1200°F. None of these alloys are particularly outstanding. Figure 65 presents 0.2% offset yield strength-to-weight ratio figures for A110 titanium alloy Inconel X, 17/7 PH-A stainless steel, as well as recrystallized tungsten. It snows that on a strength weight basis, as temperatures approach 1200°F, recrystallized tungsten is inferior to Inconel X. Figure 66 is a presentation of similar data for 301 fully hardened stainless steel, for titanium 140 alloy and for 301 stainless steel in a half hardened condition. It is seen that as the temperature approaches 1200°F, 301 fully hardened stainless is superior to the other alloys.

Figure 67 presents ultimate tensile strength to weight ratio for A110 titanium alloy, Inconel X, super alloy Stellite 25. It is
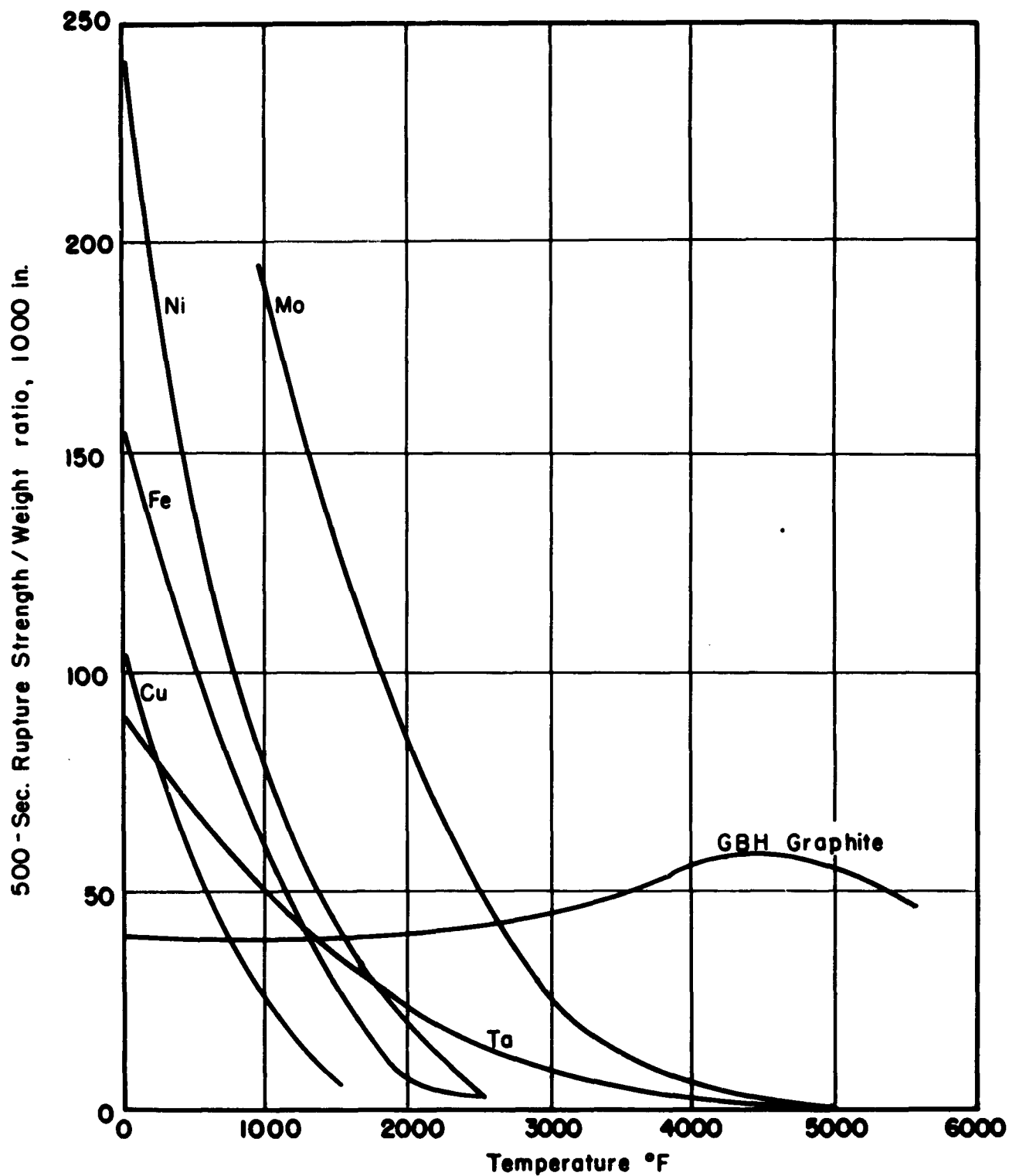
Figure 58 Effect of temperature on 500-sec rupture strength of various test materials in different types of tests in argon atmosphere (adapted from WADC TR 57-649 Pt I).
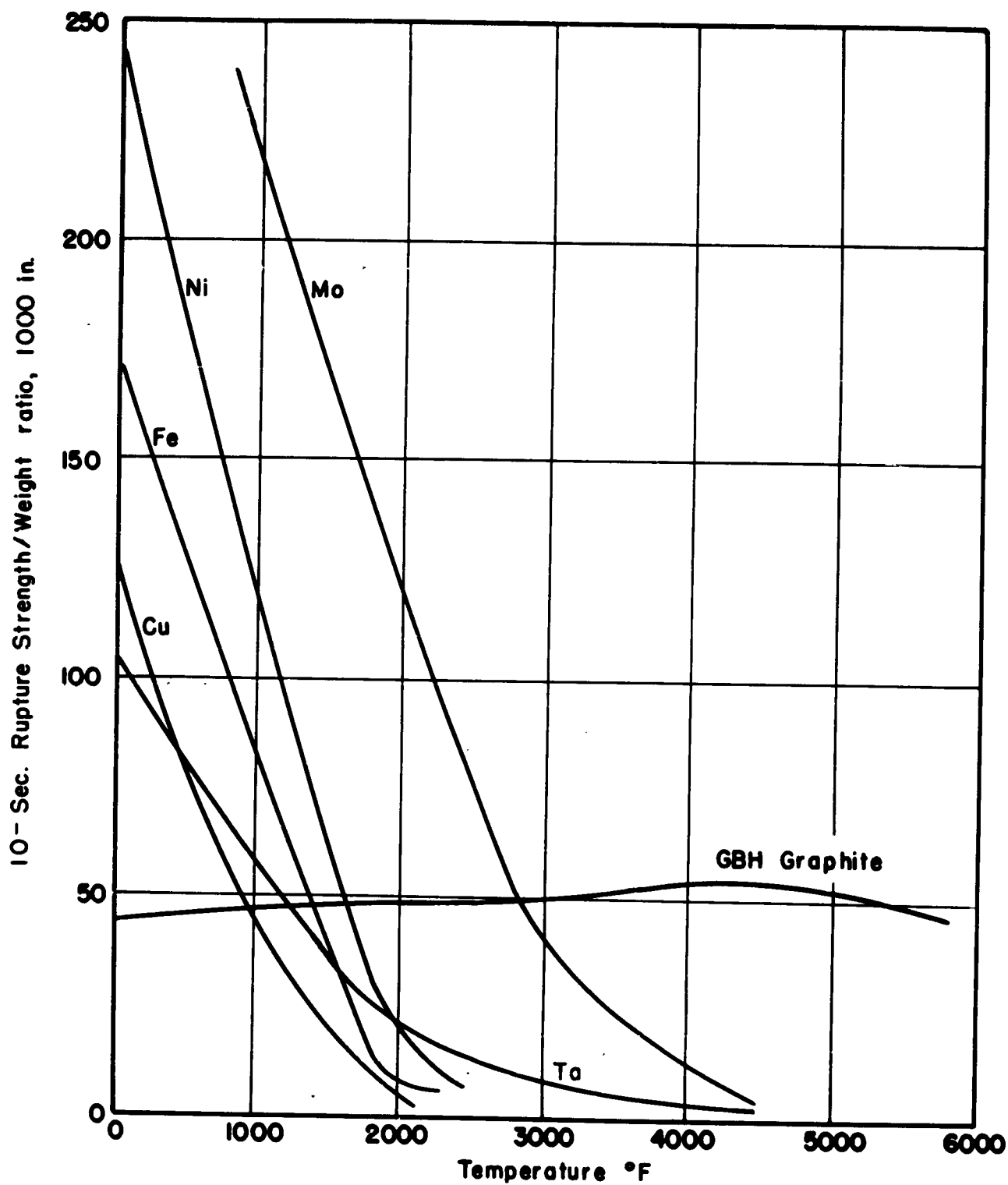
Figure 59  Effect of temperature on 10-sec rupture strength
of various test materials in different types of
tests in argon atmosphere (adapted from WADC TR
57-649 Pt I).
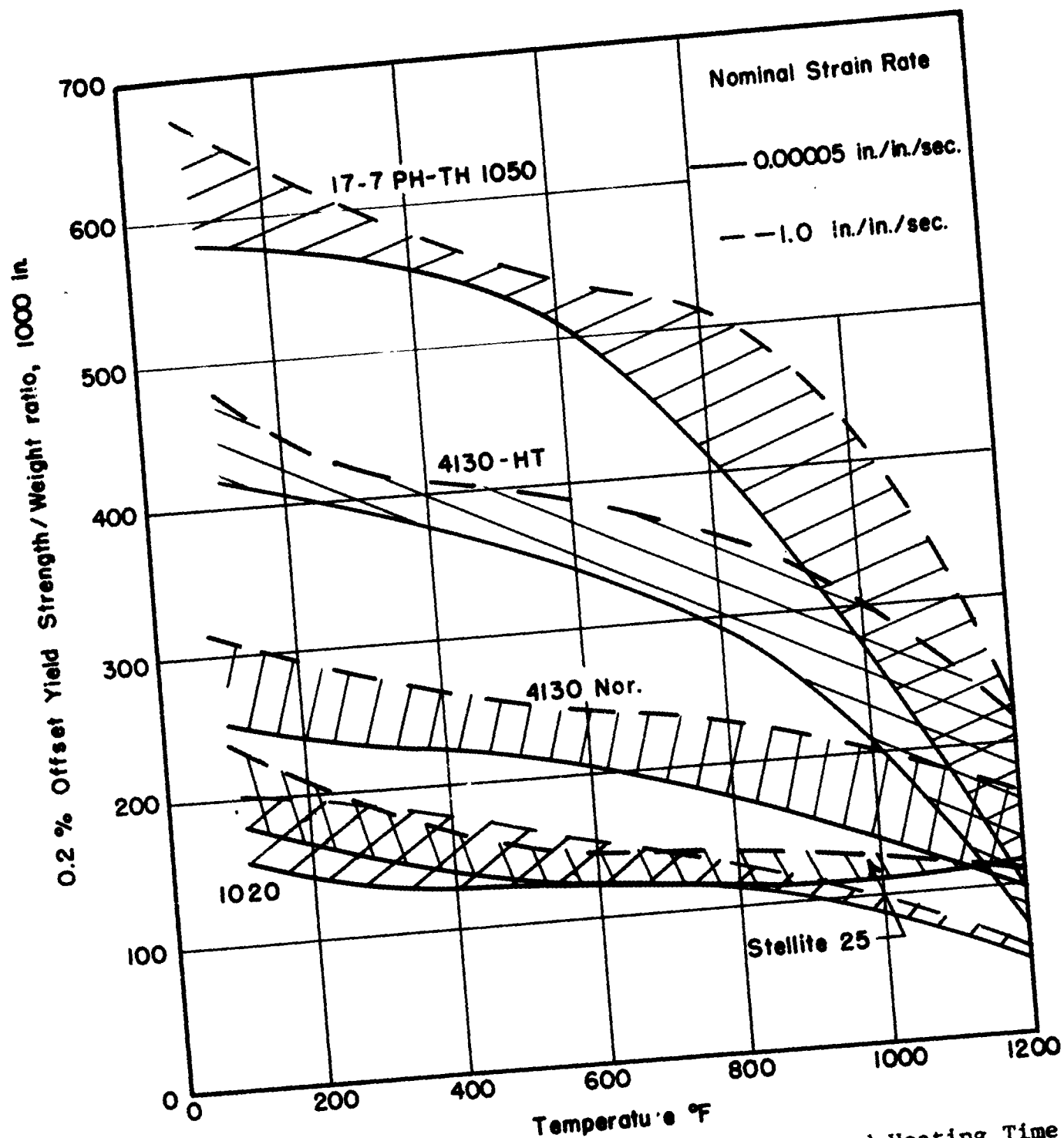
Figure 60 Effect of Temperature After 10-Second Heating Time and 1800-Second Holding Time on the 0.2%-Offset Yield Strength of Several Test Metals Over a Range of Strain Rates from 0.00005 to 1.0 in./in./sec. (adapted from WADC TR 55-199 Pt 2).

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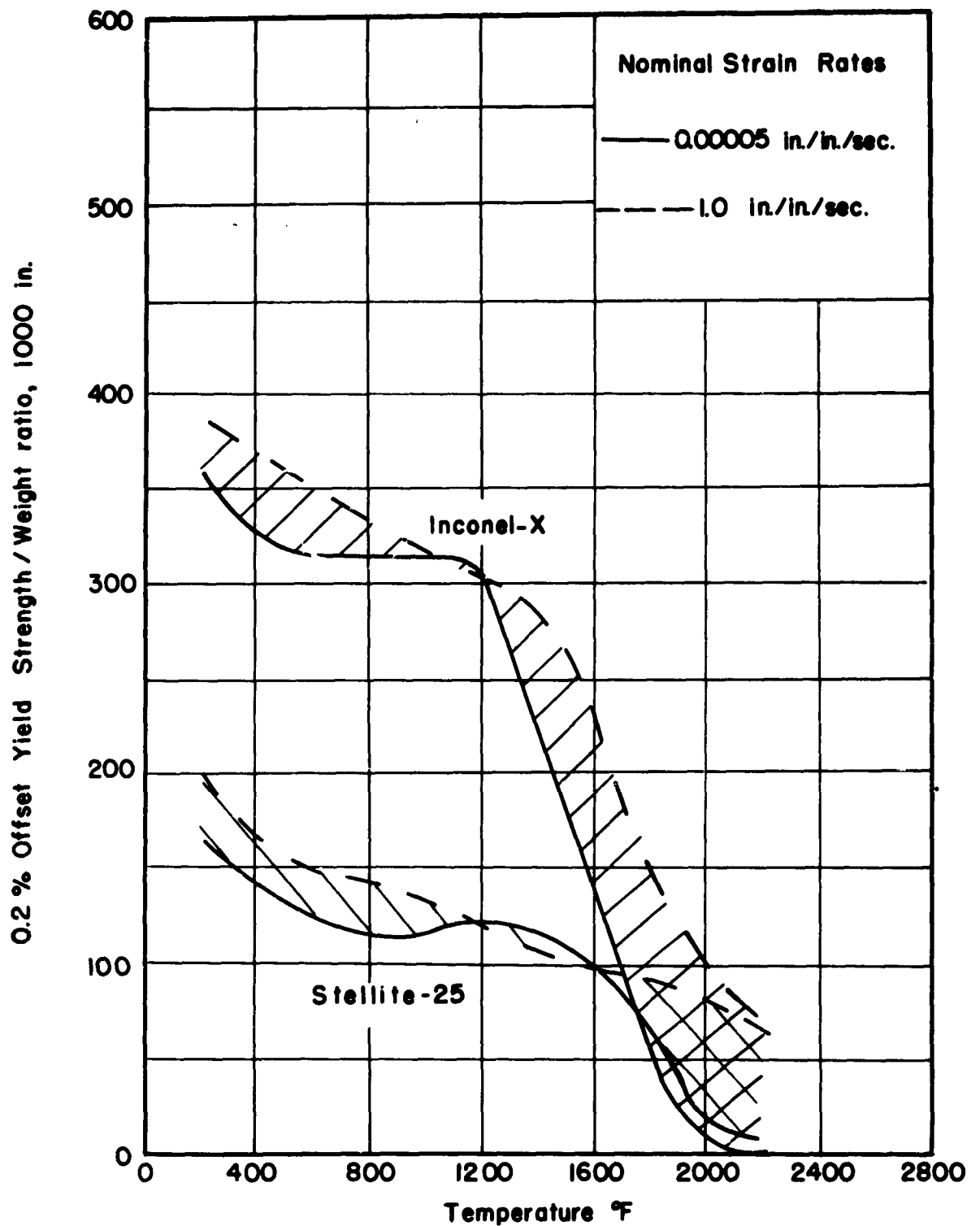
Figure 61   Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the 0.2%-offset yield strength of test metals over a range of strain rates from 0.00005 to 1.0 in./in./sec. (adapted from WADC TR 55-199 Pt III).
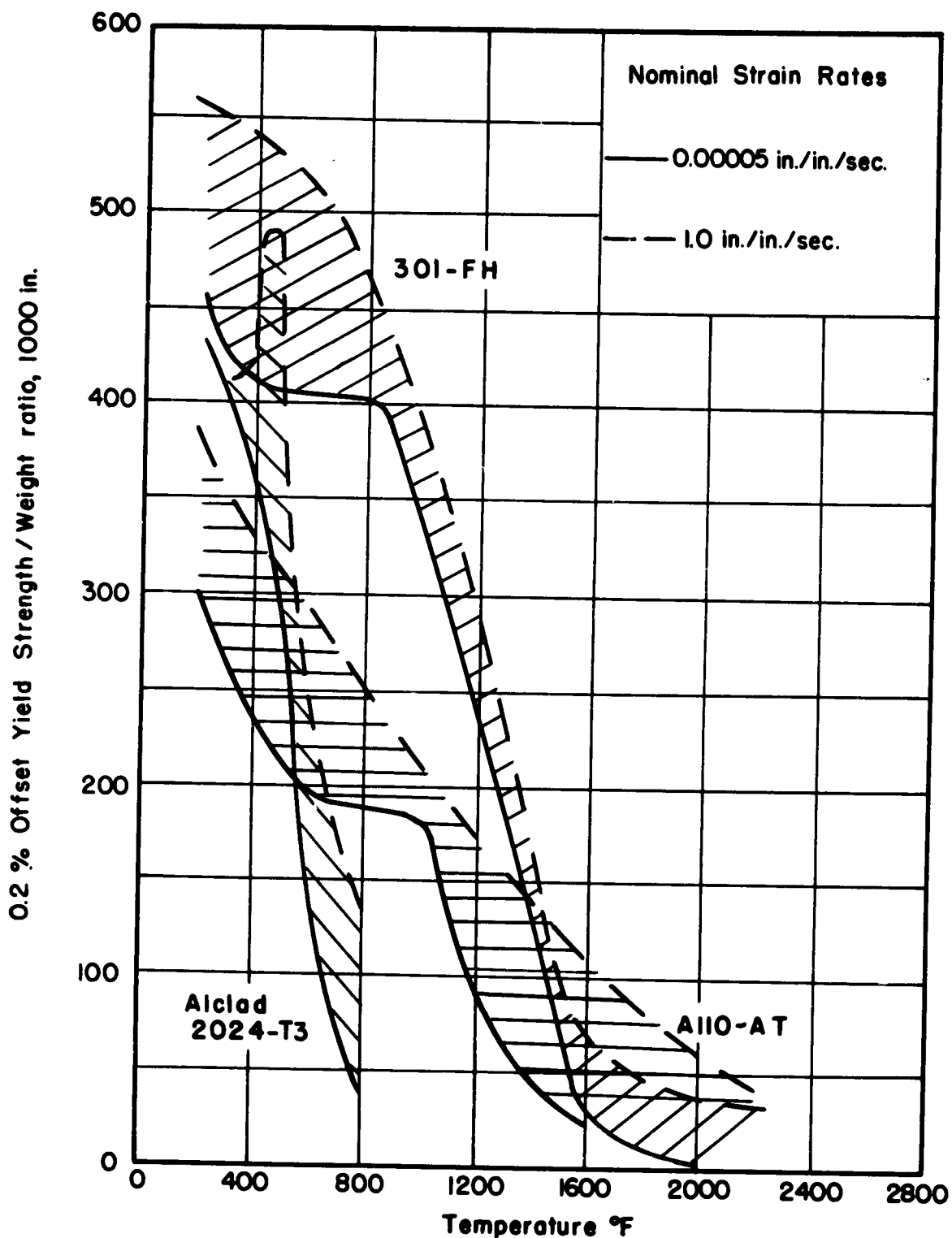
Figure 62  Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the 0.2%-offset yield strength of test metals over a range of strain rates from 0.00005 to 1.0 in./in./sec. (adapted from WADC TR 55-199 Pt III).
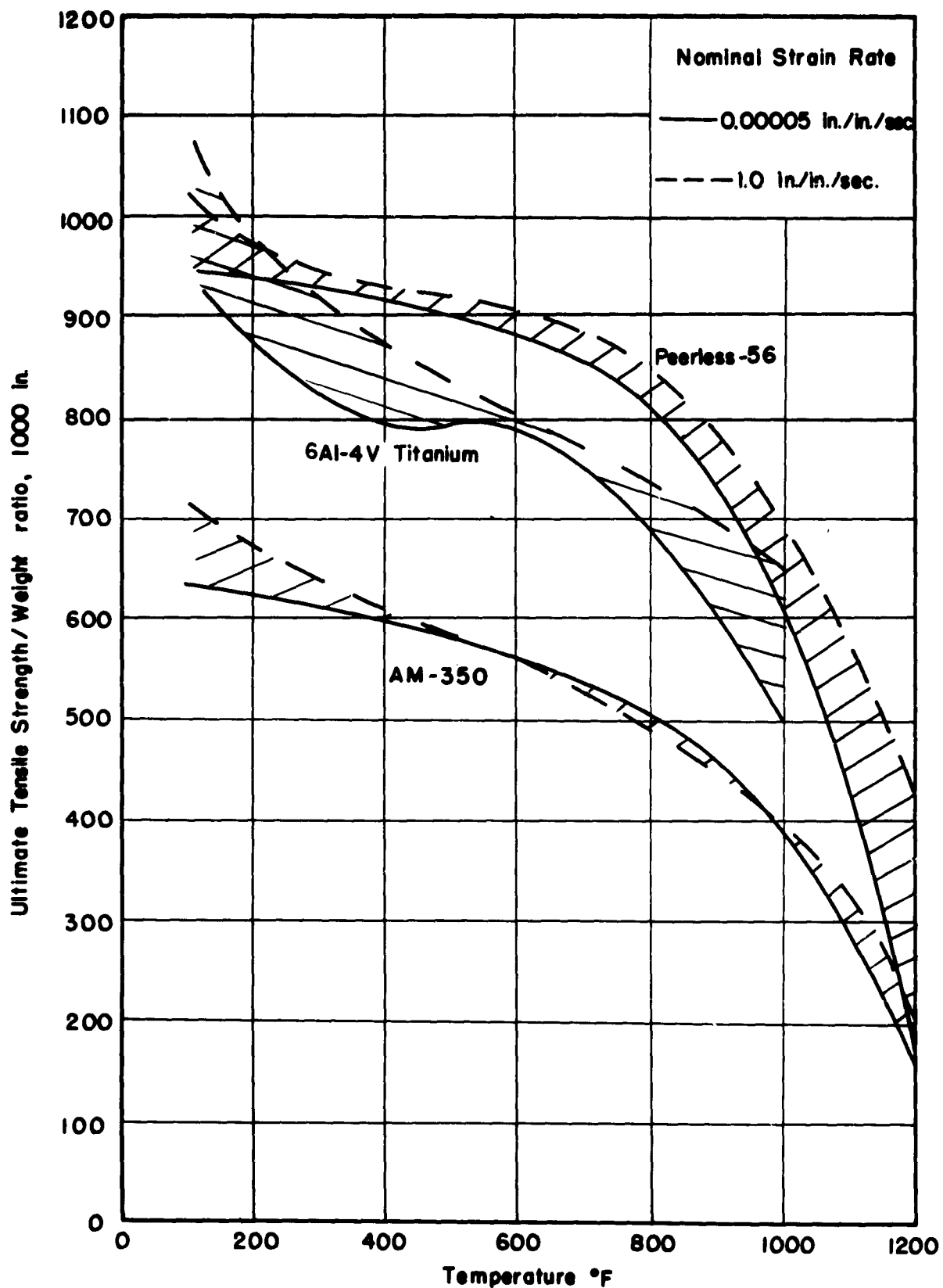
Figure 63   Effect of temperature, after 10-sec heating time and
1800-sec holding time, on the ultimate tensile strength
of test metals over a range of strain rates from 0.00005
to 1.0 in./in./sec. (adapted from WADC TR 58-440 Pt 1).
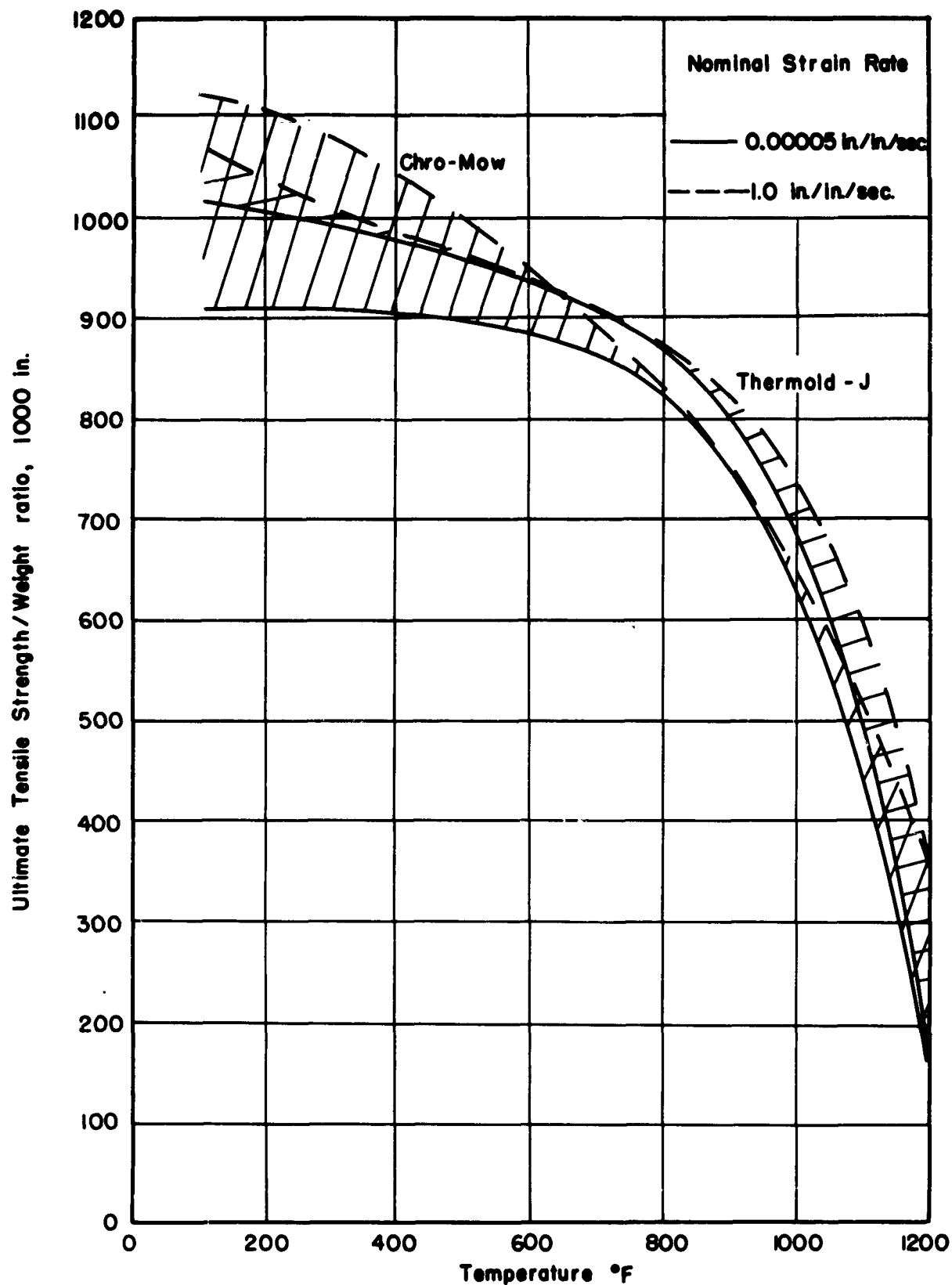
Figure 64   Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the ultimate tensile strength of test metals over a range of strain rates from 0.00005 to 1.0 in./in./sec. (adapted from WADC TR 58-440 Pt 1).
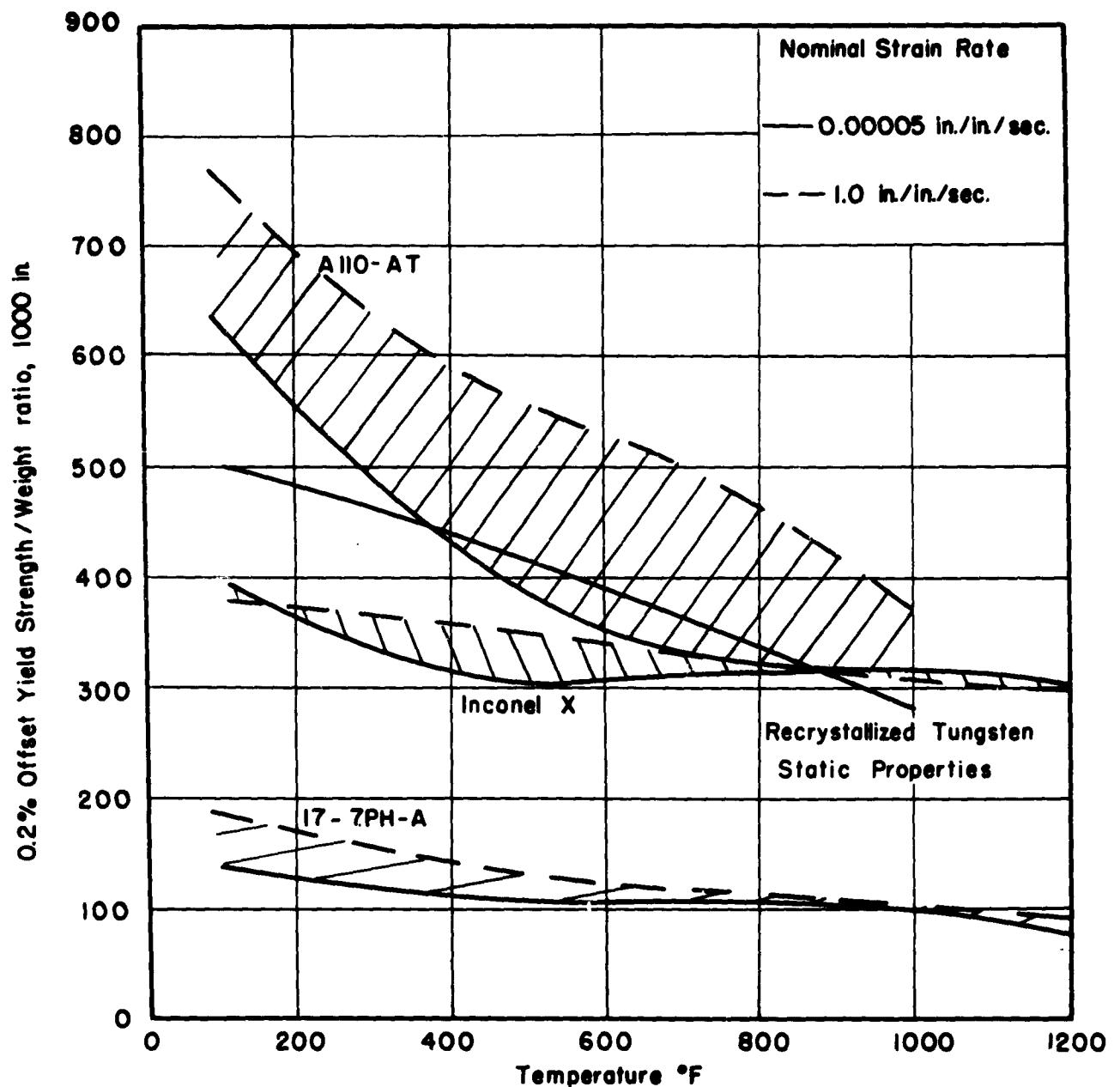
Figure 65    Effect of Temperature After 10-Second Heating Time
and 1800-Second Holding Time on the 0.2%-Offset
Yield Strength of Several Test Metals Over a Range
of Strain Rates from 0.00005 to 1.0 in./in./sec.
(adapted from WADC TR 55-199 Pt 2).
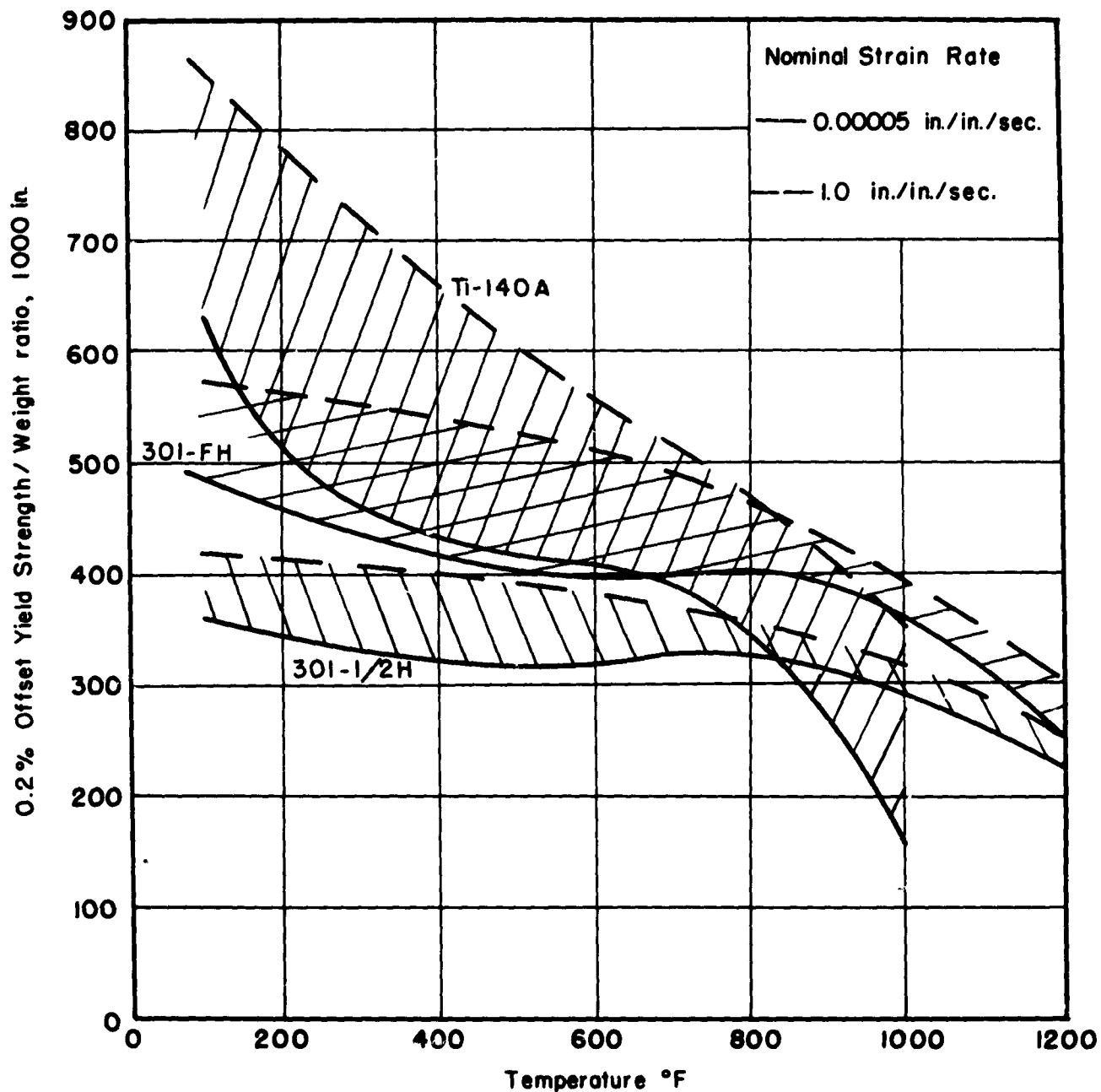
Figure 66    Effect of Temperature After 10-Second Heating Time
and 1800-Second Holding Time on the 0.2%-Offset
Yield Strength of Several Test Metals Over a Range
of Strain Rates from 0.00005 to 1.0 in./in./sec.
(adapted from WADC TR 55-199 Pt 2).
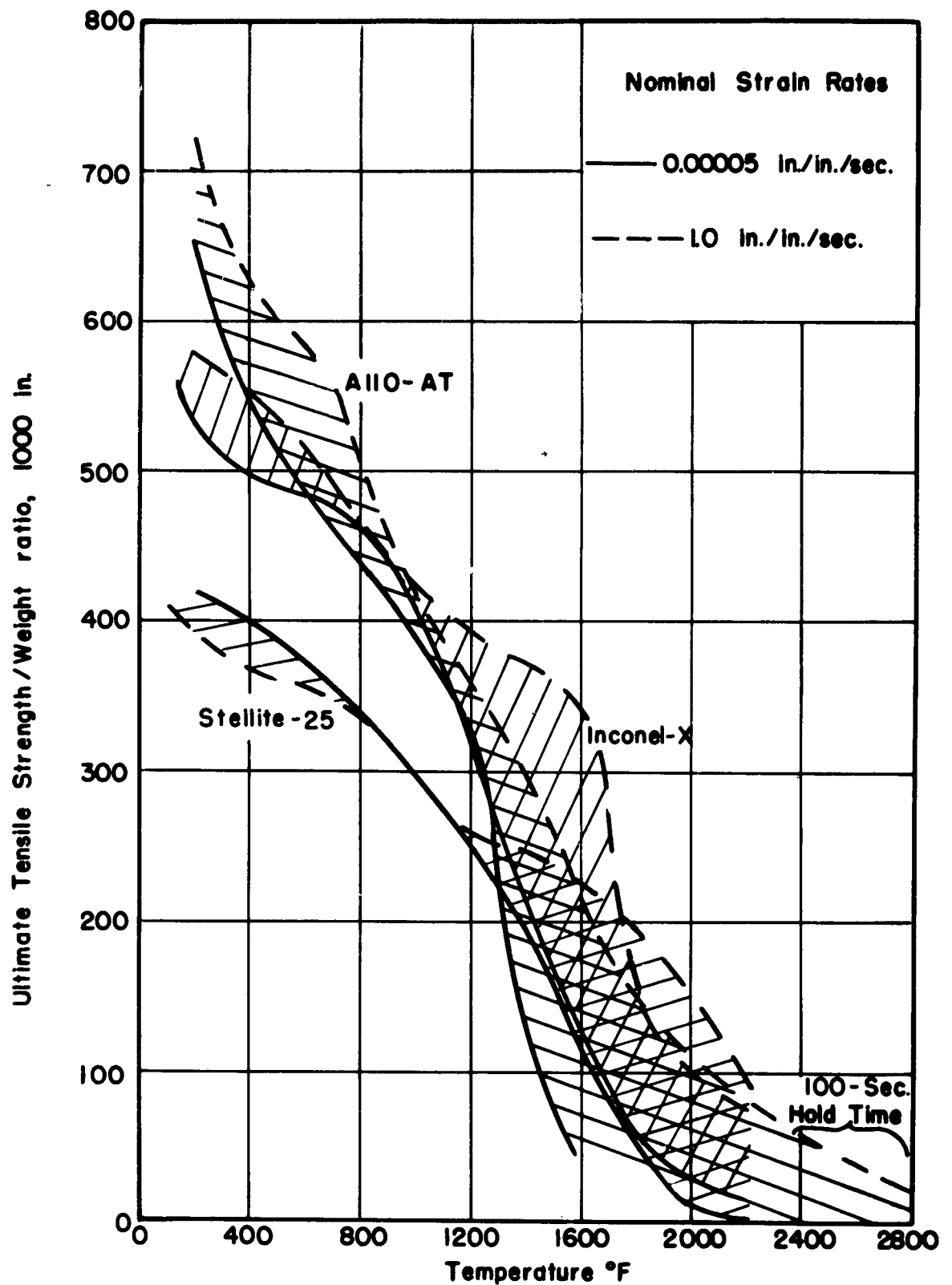
Figure 67 Effect of temperature, after 10-sec heating time and 1800-sec holding time, on the ultimate tensile strength of test metals over a range of strain rates from 0.00005 to 1.0 in./in./sec. (adapted from WADC TR 55-199 Pt III).

seen that at 1500°F, Inconel X is as good as or superior to the other two materials. Figure 68 is a similar curve for 301 fully hardened stainless steel, as well as an aluminum alloy. Comparison of this curve with Figure 67, shows that the stainless steel 301 fully hardened is as good as Inconel X at low strain rates. Figure 69 presents ultimate strength to weight ratio data for precipitation hardening stainless steel, several ferritic steels and Stellite 25 up to 1200°F, as do Figures 70 and 71. Figure 72 is very interesting, being an ultimate strength to weight ratio comparison up to 1200°F of a titanium alloy, fully hardened stainless steel, Inconel X and unrecrystallized tungsten. The titanium stainless and Inconel are all vastly superior on a strength to weight ratio comparison to unrecrystallized tungsten. The fully hardened stainless seems to be nearly as good as the Inconel. Other metals are similarly compared in Figure 73.

If the foregoing are summarized, the following may be said. For a strength-weight ratio of a 140,000 psi or better for the 0.2% offset yield at 1500°F, one must use Inconel X, 301 fully hardened stainless steel or A110 titanium alloy at high stress rates. For an ultimate strength to weight ratio of 300,000 or better at 1500°F, Inconel X or 301 fully hardened stainless must be used. It is apparent, therefore, that the stainless steels as a class are very attractive for use in drag devices. The material is readily available, it is readily fabricated and metallurgically it is well understood, both by the suppliers and the users. There is, unfortunately, no data available on 316 stainless steel which is a special high temperature variety containing molybdenum. However, it seems that it is reasonable to make the general statement that the stainless steels as a class of material look extremely promising and that further experimentation ought to be carried out, both on 301 fully hardened stainless and on 316 stainless steel containing molybdenum.
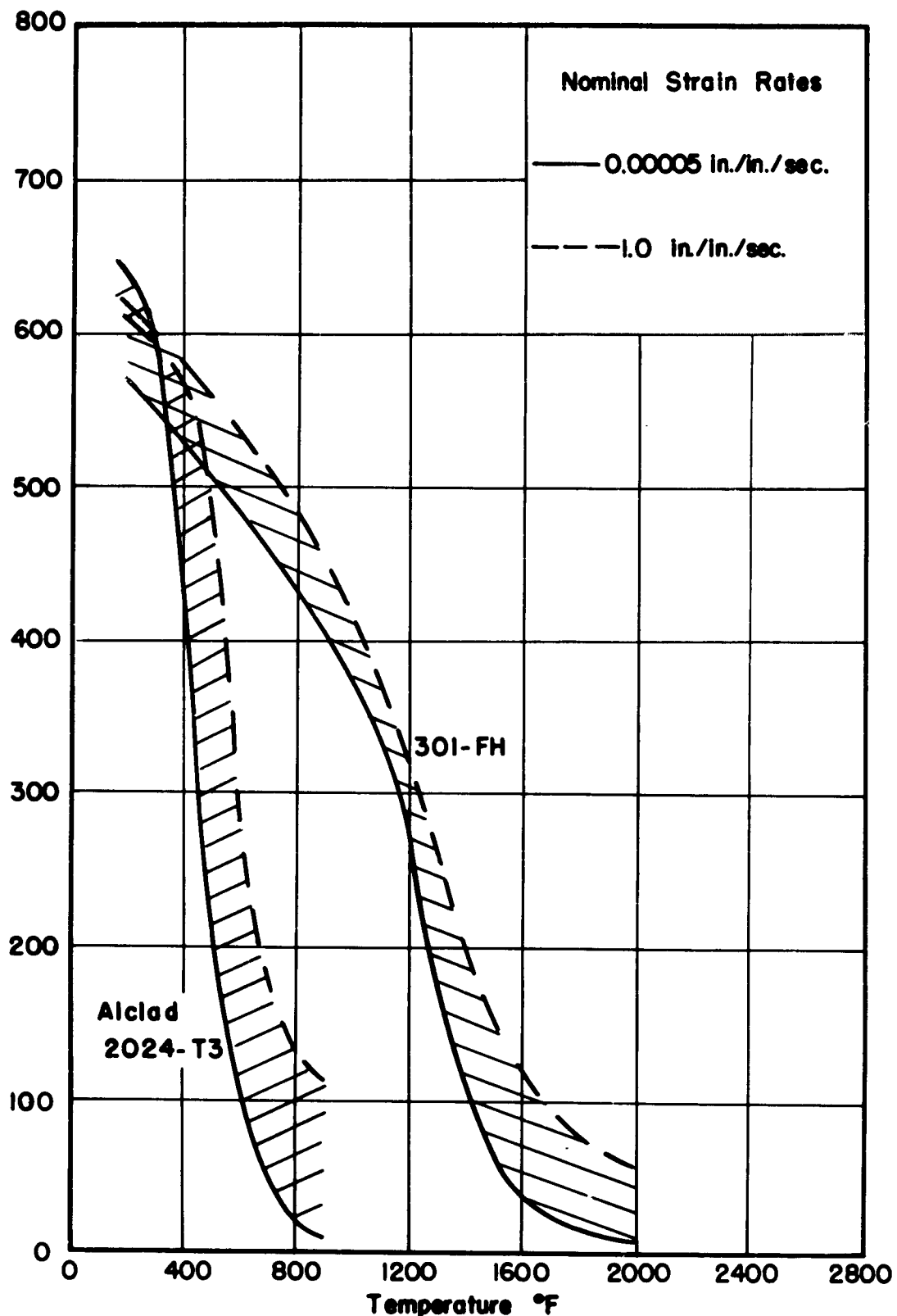
Figure 68  Effect of temperature, after 10-sec heating
time and 1800-sec holding time, on the ulti-
mate tensile strength of test metals over a
range of strain rates from 0.00005 to 1.0 in./
in./sec. (adapted from WADC TR 55-199 Pt III).
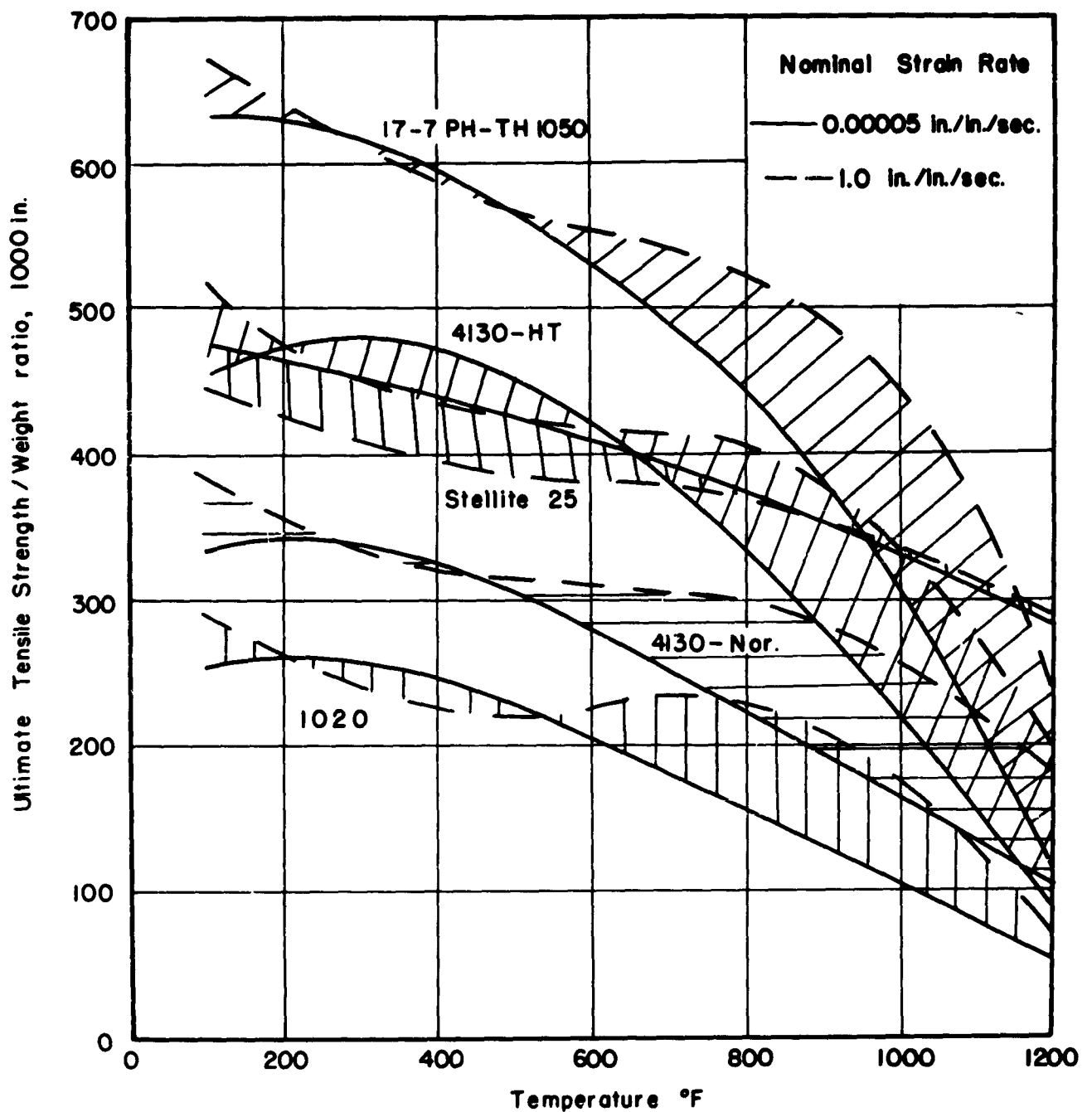
Figure 69    Effect of Temperature After 10-Second Heating Time
and 1800-Second Holding Time on the Ultimate Tensile
Strength of Several Test Metals Over a Range of
Strain Rates from 0.00005 to 1.0 in./in./sec.
(adapted from WADC TR 55-199 Pt 2).
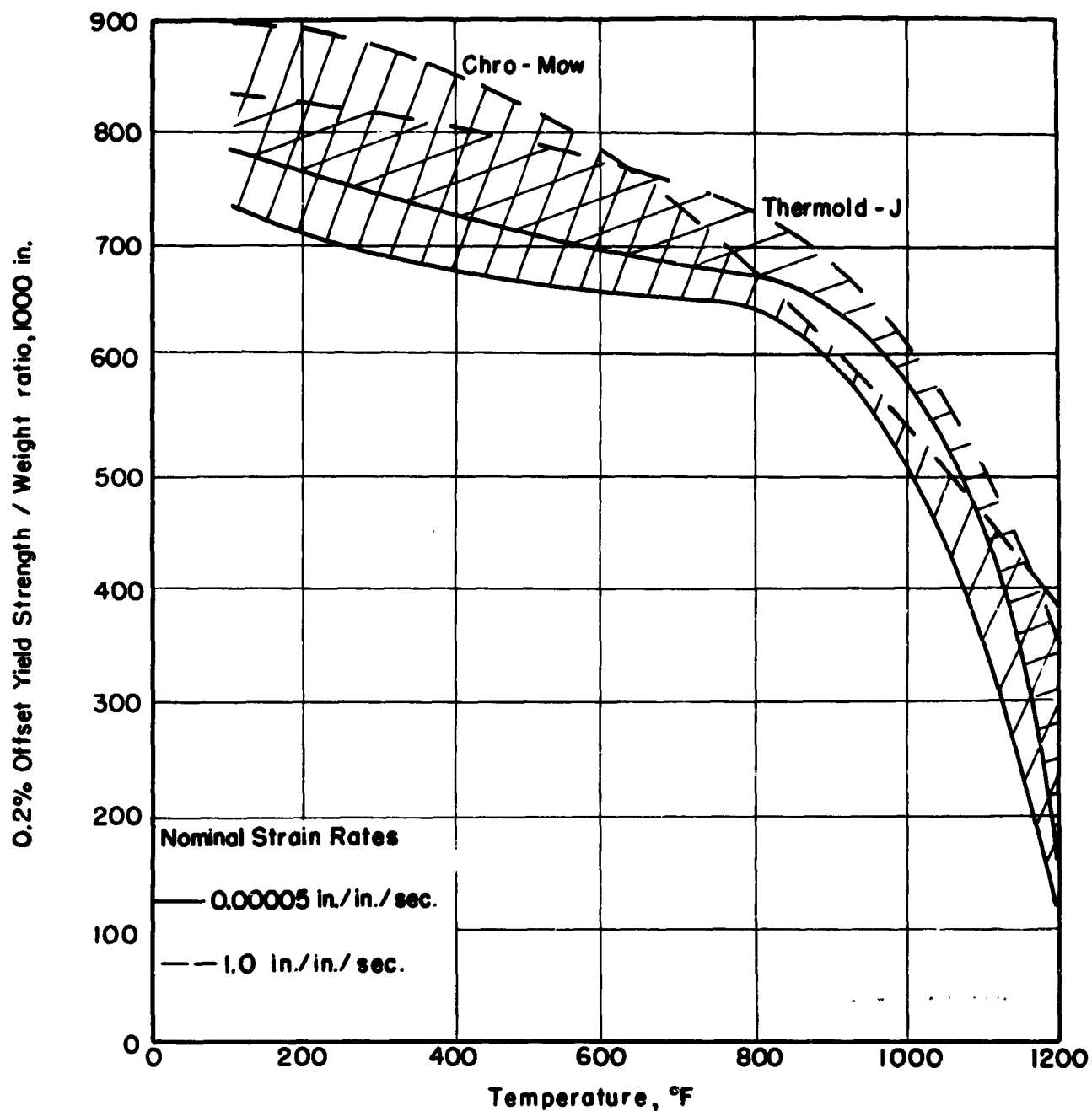
Figure 70    Effect of temperature, after 10-sec heating time
and 1800-sec holding time, on the 0.2%-offset
yield strength of test metals over a range of
strain rates from 0.00005 to 1.0 in./in./sec.
(adapted from WADC TR 58-440 Pt 1).
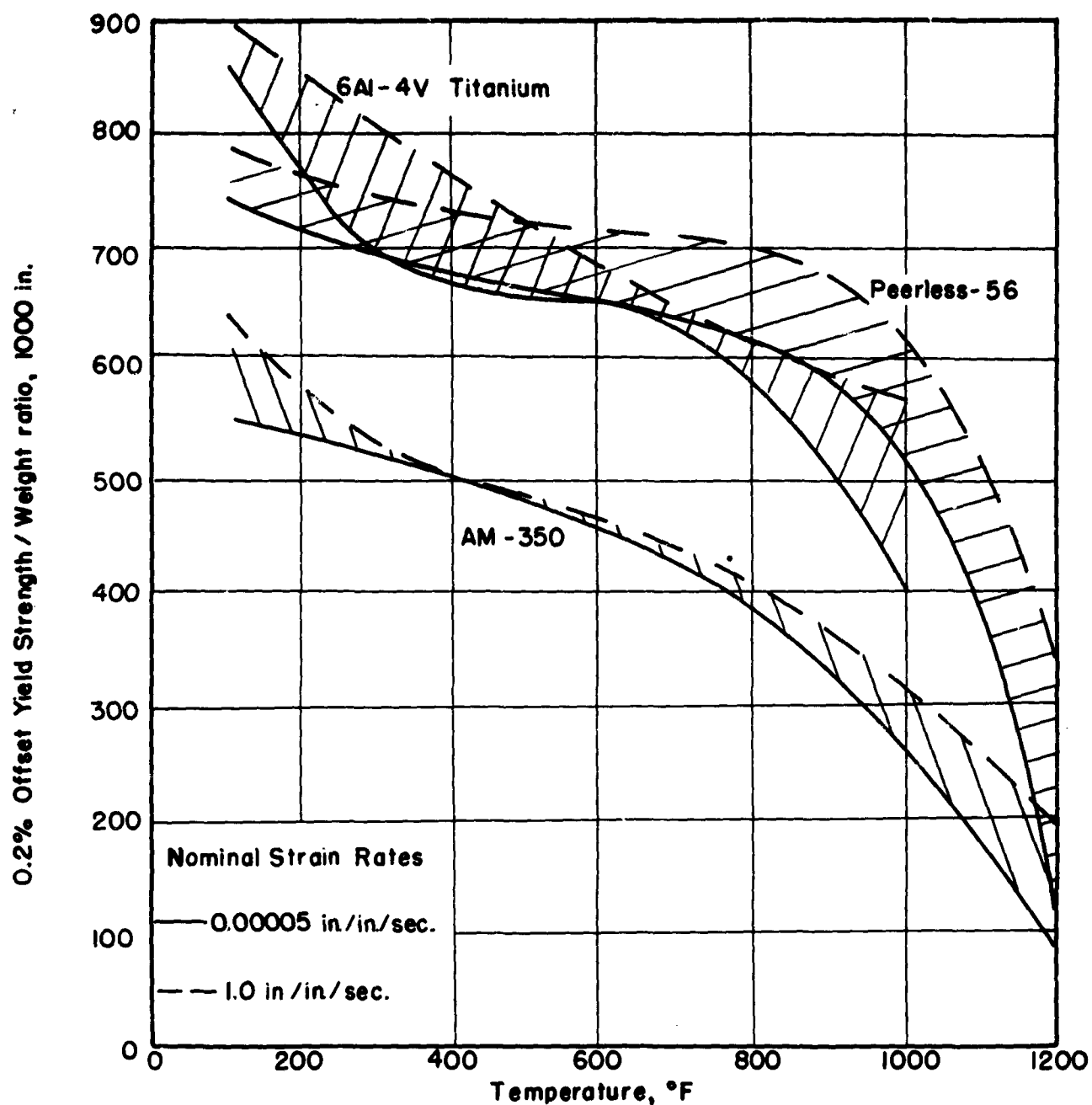
Figure 71    Effect of temperature, after 10-sec heating time
and 1800-sec holding time, on the 0.2%-offset
yield strength of test metals over a range of
strain rates from 0.00005 to 1.0 in./in./sec.
(adapted from WADC TR 58-440 Pt 1).
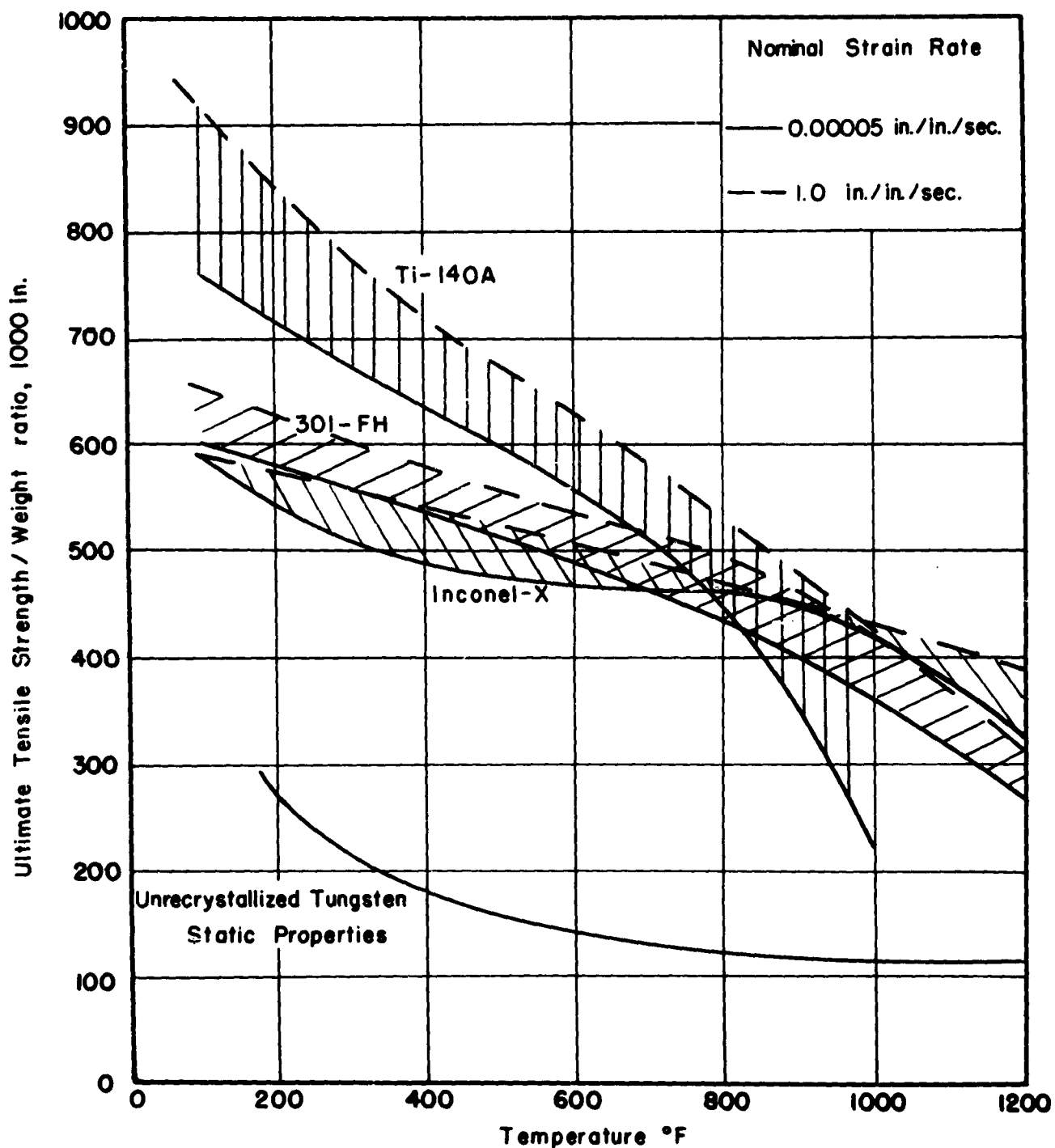
Figure 72    Effect of Temperature After 10-Sec Heating Time and
1800-Sec Holding Time on the Ultimate Tensile
Strength of Several Test Metals Over a Range of
Strain Rates from 0.00005 to 1.0 in./in./sec.
(adapted from WADC TR 55-199 Pt 2).
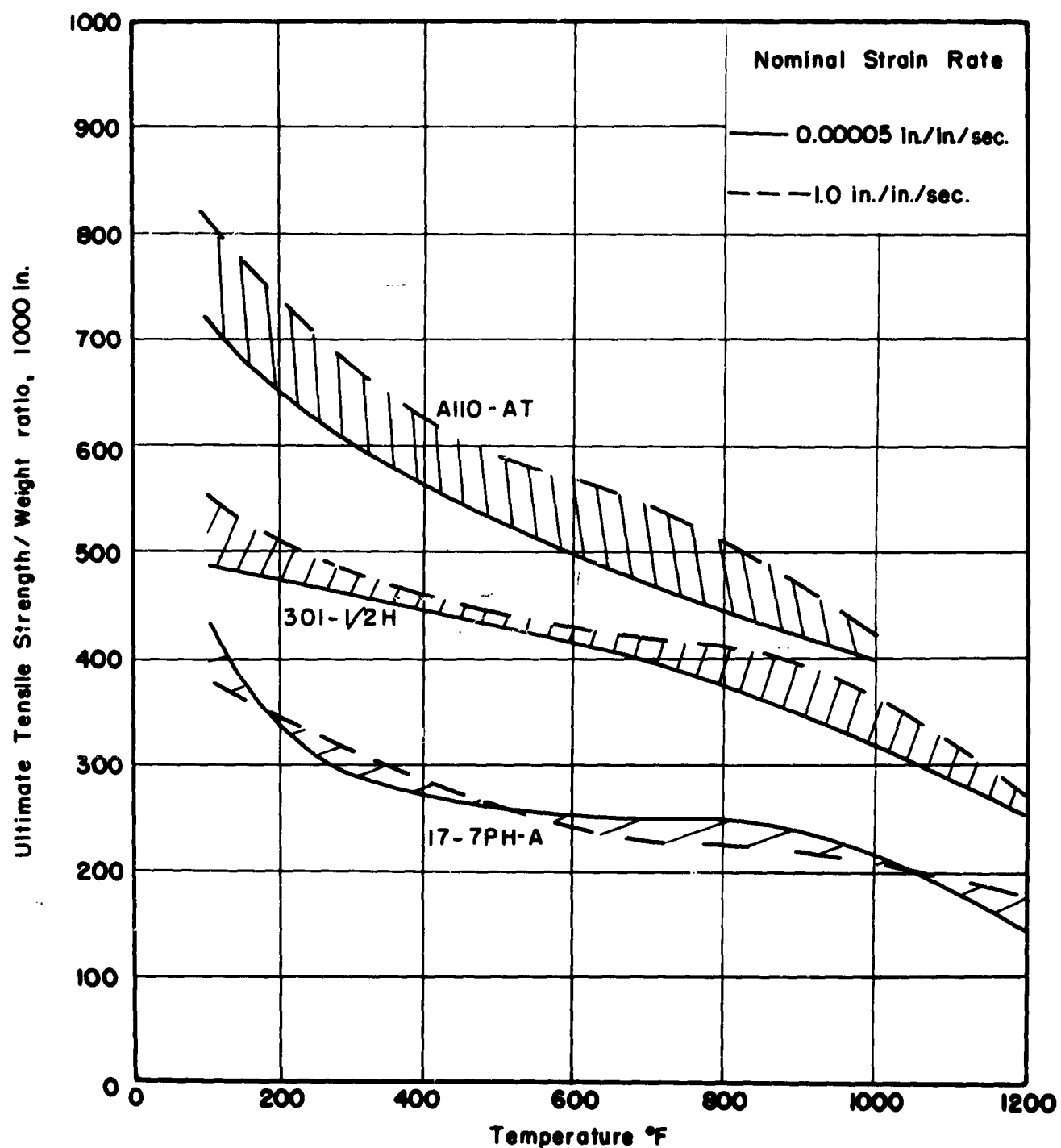
Figure 73   Effect of Temperature After 10-Sec Heating Time and
1800-Sec Holding Time on the Ultimate Tensile
Strength of Several Test Metals Over a Range of
Strain Rates from 0.00005 to 1.0 in./in./sec.
(adapted from WADC TR 55-199 Pt 2).

A.    METALS (Continued)

     5.    Protective Coatings*

     Normal tendency would be to choose a coating metal on the
basis of its oxidation resistance and bulk properties derived in
metallurgical studies.  Such studies show which metals could not
provide the protection desired, but would only indicate those
which might be heat tolerant as coatings.  The properties of a
metal vary according to the method of applying it as a coating
and according to the physical and mechanical state of the basic
metal to be coated.  The effects are particularly seen in the
behavior of a coating during its first cycles of heating and
cooling.

     Also, the properties of the composite structure, bulk-basic
metal different-metal-surface, will depend on the formation of a
diffusion alloy zone and on the properties of such an alloy zone
between the coating and the basic metal.

     The word coating usually implies an intimate or "skin tight"
covering applied after a part or structure is in its final bulk
form.  On the basis of properties at very high temperature,
methods of application, and properties of their alloys, the metals
in Table 6 have received the most attention as coatings.  The
temperature to be reached in service, the time at temperature,
and the size and complexity of the part will indicate which of
the metals is a coating prospect and which of the processes should
be used for applying the coating.  The following factors determine
whether the coating will provide the desired heat tolerance:

     Oxidation (and/or corrosion) resistance.
     Thermal stability
     Coefficient of thermal expansion relative to that of the
basis metal.
     Propensity for diffusion alloying with the basis metal at
the interface.
     Properties of such a diffusion alloy zone relative to the
performance needs.


*This section is based almost entirely on excerpts from Faust,
C.L., Protective Metallic Coatings, Chapter 5 in Metals for Super-
sonic Aircraft and Missiles, A.S.M., 1958.

# TABLE 5 - OXIDATION RESISTANT COATINGS FOR ELEVATED TEMPERATURES

| Coating | Methods for Application | Temperature of Rapid oxidation*** | |
|---|---|---|---|
| | | °C | °F |
| Aluminum*<br>mp 660°C | Hot dipping<br>Metal spraying<br>Aluminum paint,<br>plus heat diffuse<br>Electroplating<br>Vapor plating | 500 to 1100 | 935 to 2000 |
| Chromium<br>mp 1890°C | Electroplating<br>Vapor plating | 1100 to 1700 | 2000 to 3100 |
| Cobalt<br>mp 1495°C | Electroplating<br>Electroless plating<br>Vapor plating<br>Spraying | 800 to 1100 | 1470 to 2000 |
| Gold<br>mp 1063°C | Electroplating | | |
| Iron<br>mp 1539°C | Electroplating<br>Vapor plating<br>Spraying | 500 to 800 | 935 to 1470 |
| Nickel<br>mp 1455°C | Electroplating<br>Electroless plating<br>Vapor plating<br>Metal spraying | 1100 to 1400 | 2000 to 2550 |
| Niobium<br>mp 2415°C | Vapor plating | 500 to 800 | 935 to 1470 |
| Platinum<br>mp 1773°C | Electroplating<br>Vapor plating | Above 1700 | Above 3100 |
| Rhenium<br>mp 3170°C | Electroplating<br>Vapor plating | 500 to 800 | 935 to 1470 |
| Rhodium<br>mp 1966°C | Electroplating<br>Vapor plating | Above 1700 | Above 3100 |
| Silicon<br>mp 1430°C | Vapor plating | 1100 to 1400 | 2000 to 2550 |

TABLE 6 (Cont.)

| Coating | Methods for Application | Temperature of Rapid oxidation*** | |
|---|---|---|---|
| | | °C | °F |
| Tantalum mp 3000°C | Vapor plating | 500 to 800 | 935 to 1470 |
| Titanium mp 1820°C | Vapor plating Electroplate, fused salt | 1100 to 1400 | 2000 to 2250 |
| Tungsten mp 3410°C | Vapor plating Electroplating, alloys | 800 to 1100 | 1470 to 1830 |
| Vanadium mp 1735°C | Vapor plating | 800 to 1100 | 1470 to 1830 |
| Zirconium mp 1830°C | Vapor plating | 1100 to 1400 | 2000 to 2550 |
| Chromium- nickel alloy** | Electroplating, plus diffusion Vapor plating | Up to 1150 | Up to 2100 |
| Chromium- aluminum alloy** | Vapor plating Electroplating, plus diffusion | | |
| Chromium- aluminum- nickel alloy** | Vapor plating Electroplating, plus diffusion | Up to 1150 | Up to 2100 |
| Gold- chromium alloy** | Electroplating, plus diffusion | | Up to 1800 |

*Aluminum as such usually fails by erosion rather than oxidation. However, by alloying as to form an aluminum-iron compound by diffusion into an iron basis metal, the resulting coating can resist oxidation up to 2110°F for a short time, as demonstrated by its use as a coating on V-2 rockets. **The temperature limits are estimates. ***See references 2.

Melting point of the coating and of the diffusion alloy zone.

## Methods of Applying Coatings

As shown in Table 6, several methods are available for applying coatings. Chemical reduction (electroless plating), electroplating, metal spray, and vacuum vaporizing do not subject the basis metal to high temperatures. The coatings are applied at near ambient atmospheric temperatures and undergo the first heating effects while reaching service temperature for the initial run. Electrodeposited coatings will differ in behavior somewhat from those of the same metal by spraying, and both types will differ from coatings applied by hot dipping and by vapor plating.

Within the general ranges of procedure for electroplating, variations in plating bath type and composition contribute to large differences in stress, crystal structure, grain size, inclusions, and freedom from pores in the plate, and contribute to differences in stability at high temperature.

Hot dipping usually subjects the basis metal to a temperature slightly above the melting temperature of the coating metal; for example, 1220°F (660°C) for aluminum. Vapor plating can be done at a comparatively low temperature using organometallic volatile compounds of some metals, but it may range to as high as 2650°F (1400°C) for vapor plating with the halide of a highly refractory metal. Hot dip coatings always have a diffusion alloy layer between the basic metal and the coating. Coatings vapor plated at a high temperature will either have such an alloy zone or be entirely a surface alloy of the basic metal and the coating metal (or element, in the case of nitrides, carbides, borides, and · silicides).

Commercial processes have been developed for applying nickel coatings up to 0.005 in. or more in thickness by electroless plating (chemical reduction). The coatings contain 5 to 8% phosphorous. Coatings of cobalt and cobalt-nickel alloy and of chromium have been applied by similar processes. Only the nickel processes is at the stage for large-scale application (3).

Methods of electroplating with the metals, as named in Table 6 are in large-scale use and have been well developed (4), (5) for aqueous electrolytes. Fused-salt electrolytes for electroplating

with molybdenum, zirconium, and titanium, are not at the com-
mercial stage of development. Electrodeposited coatings for
protection against oxidation are 0.002 to 0.005 in. thick or
thicker.

Aluminum is the only metal of heat tolerance interest that
is applied by hot dipping. Coating thicknesses are usually
about 0.001 in. but may go up to 0.005 in. with an alloy zone
interface from 0.0002 to 0.002 in. thick.

Metal spraying, or painting on aluminum powder, usually
applies coatings that are porous and require reworking to achieve
optimum properties. This requirement cannot be met in filament
treatment. Further such techniques tend to alter significanlty
the desirable filament properties.

Coatings by vapor plating can be applied usually from a few
millionths of an inch to 0.1 in. in thickness. (2) The average
coating is in the range of 0.001 to 0.010 in. thick. The tem-
perature of the basic metal determines whether a dense non-
porous coating, a coarsely crystalline structure, or adherence
or nonadherence is produced.

Vacuum evaporation applies such thin coatings and is so slow
as to probably be of little importance now. However, the coating
thickness of less than 0.00001 in. may be enough where diffusion
alloying produces the protective coating. Furthermore the
problems of obtaining continuous uniform coatings on fine fila-
ments are numerous.

Oxidation Resistance. The principal reason for using protect-
ive coatings is to provide resistance to reaction with oxygen,
nitrogen, and other constituents of air or other aerodynamic at-
mospheres. The response will be somewhat independent of the
method of coating, but special situations exist.

The oxidation resistance of a number of electrodeposited
metals in air is shown in Table 7 (6). The section, "Possible
Electroplates" in Table 7, refers to good prospects. Gold and
platinum coatings, of course, can be applied by electro-deposition.
Nickel-chromium-aluminum alloy coatings also should be attainable
by electrodepositing multi-layer coatings of the individual metals
and diffusion alloying. The required heating subjects the basis
metal to the same treatment that may be limiting as to which basic
metals can be so coated.

The initial rate of oxidation can differ for stressed and unstressed surface metal. Experimental results show that oxide in an electroplate can increase the oxidation rate at very high temperatures (6).

According to data in Table 7 chromium-iron alloy plate (7) oxidized somewhat slower than nickel and chromium in air at 1800°F, whereas, these three plates oxidized much slower than the cobalt-tungsten. The nature of the scales were different (6). Such differences in scale brittleness and spalling tendency will be critical in coatings applied to fine filaments.

Vapor-plating studies have shown the oxidation resistance of a number of the metals in Table 6 (2). Chromium is superficially oxidized at about 2720°F (1500°C). The alloy surface, resulting from chromizing iron by a vapor-plating process or from diffusion at high temperatures, resists oxidation up to 1640°F (900°C). Aluminum in the coating increases the temperature limit to 1820 to 1910°F (1000 to 1050°C). Chromium absorbs hydrogen and nitrogen which harden it and decrease its ductility, a limiting condition for filament coating.

Molybdenum is rapidly oxidized in air at 1110°F (600°C), a volatile oxide being formed. Carbon is absorbed to form carbide that hardens and embrittles the molybdenum, which, however, is not affected by hydrogen and nitrogen. Thus, for very high temperatures in air, molybdenum is not a prospect for a protective coating but is itself in need of a protective coating.

Platinum is not attacked in air up to the melting point nor by single acids. Iridium forms a volatile oxide above 1280°F (700°C) and rhodium superficially oxides at about 1460°F (800°C). The rhodium oxide decomposes at about 2190°F (1200°C). None of these coatings appear to hold promise for filament application.

Rhenium an extremely refractory metal, can be applied by vapor plating the basic metal which is heated to 1820 to 2190°F (1000 to 1200°C). Resistance to oxidizing gas is about the same as that of tungsten (2). Rhenium is not affected by hydrogen or nitrogen at high temperatures and is unique in not forming a carbide at high temperatures. This coating, with further development, has possibilities in filament applications.

Tungsten oxidizes rapidly at red heat in air and acquires a porous oxide coating. Hydrogen and nitrogen are not absorbed in

## TABLE 7 -- OXIDATION RATES OF ELECTROPLATES USEFUL AS HEAT TOLERANT COATINGS IN AIR

| Electroplate | Oxidation Rate at 1800°F, Mg per Sq Cm per Hr Total Exposure | | |
|---|---|---|---|
| | 10 Hr | 50 Hr | 100Hr |
| Chromium | 0.7** | No data | 0.28 |
| Chromium-5% iron | 0.6 | No data | 0.20 |
| Chromium-18% iron | 0.6 | No data | 0.26 |
| Cobalt | 7.2* | No data | No data |
| Cobalt-27% tungsten | 5.8 | No data | 2.8 |
| Nickel | 1.0*** | No data | 0.32 |
| Nickel-20% chromium**** | 0.35 | 0.12 | 0.10 |
| **Possible Electroplates** | | | |
| Gold | None | None | None |
| Nickel-18% chromium-2% aluminum | No data | 0.01 | No data |
| Nickel-15% chromium-4% aluminum | No data | 0.02 | No data |
| Platinum***** | No data | 0.01 | No data |

*"The Fabrication and Evaluation of Thin Clad Sheetings on Molybdenum," by M.H. LaChance and R.I. Jaffee, _Transactions_, American Society for Metals, Preprint No. 43, 1955.

**Gives rate as 2.9 mg per sq cm per hr for commercial chromium plate. Above reference.

***Shows wrought A nickel oxidation rate in air as 1.3 mg per sq cm per hr. Above reference.

****Cast, wrought and annealed chromium-20% nickel alloy oxidized at 0.06 mg per sq cm per hr during a 10 hr period. Above reference.

*****"High-Temperature Corrosion of Noble Metals and Their Alloys," by E.M. Wise, _Corrosion Handbook_, 1948, p. 699.

appreciable amounts, but carbon is to produce a hard metal. Tungsten does not appear to hold promise as a filament coating.

Titanium coatings oxidize only superficially at temperatures up to 1640°F (900°C), but oxygen is absorbed at temperatures above 1290°F (700°C) resulting in hardening and embrittling of the coating, a serious disqualifying feature for filament and textile application.

The material to be vapor plated with vanadium is heated to 1820 to 2190°F (1000 to 1200°C). Vanadium coating does not improve corrosion resistance of steel so much as chromizing. For vapor plating with chromium, the basic metal is at a temperature of 1640 to 2650°F (900 to 1400°C) depending on the method used. If satisfactory filament base metals were available to stand these temperatures the parachute problem would be relatively simplified.

Niobium and tantalum may be vapor plated by hydrogen reduction of the respective chlorides at a basic metal composition of 1100 to 2650°F (600 to 1400°C). To avoid porosity, coating thickness is in the range of 0.0005 to 0.025 in. Such coating thicknesses are generally excessive for fine filament applications. Some oxygen and carbon can be removed from a basic metal during coating, so a hard, brittle interface may be formed if the base metal contains these elements. Superficial oxidation of the coating in air occurs below 750°F (400°C). This oxide is protective up to about 1470°F (800°C) where it becomes porous and no longer protective in the filament application considered here. Nitrogen is taken up at higher temperatures. Tantalum-nickel alloy is tough and corrosion resistant. Hence, a flash coating of nickel (probably by electroplating) on steel is helpful before vapor plating with tantalum.

Coatings of nitrides and carbides can be applied by vapor plating (2). The refractory nature of high-melting nitrides can be of full use only in nonoxidizing atmospheres of nitrogen. Titanium, zirconium, and hafnium carbides are stable in air at 930 to 1470°F (500 to 800°C), whereas molybdenum and tungsten carbides are oxidized. With nitrogen, the degree of attack is in the reverse order.

Coatings of borides applied by vapor plating have extreme hardness and some resist oxidation up to 1830 to 2470°F (1200 to 1300°C), although superficial oxidation may occur at lower temperatures (2). Such hardness works against satisfactory filament flexibility. Zirconium boride is fairly oxidation resistant at temperatures up to 2650°F (1400°C) and titanium boride up to 2730°F (1500°C), although a thick oxide film forms.

Refractory silicide coatings by vapor plating have prospects for protection against oxidation in air at temperatures up to their melting points: 1830 to 3630°F (1000 to 2000°C). The oxidation products contain the nonvolatile, refractory oxide, silica (2). This silica coating is unusually protective. For vapor plating with silicon, the basic material is heated to 1400 to 2190°F (770 to 1200°C). Siliconized iron is of interest for oxidation resistance at moderately high temperatures, although various factors may cause mechanical damage which limit its application in filament forms.

Siliconized molybdenum filaments heated in air at 3090°F (1700°C) had life exceeding 1000 hr, whereas uncoated molybdenum failed in seconds. Maximum resistance resulted when the coating had the composition $MoSi_2$. Failure at higher temperature occured because of silicon diffusion into the molybdemum. By modification in alloy coating, oxidation resistance above 3600°F (2000°C) can be secured. Silicide coatings of titanium, zirconium, niobium, tantalum, and tungsten show good resistance to oxidation up to 1830 to 2020°F (1000 to 1100°C), but not such good resistance as molybdenum disilicide.

Surface Metallurgy The interfacial zone between the basic metal and its protective coating can be responsible for the success or failure of the composite item. Adherence of coatings is, of course, important under the conditions of service. Also, the bond strength is a property that encompasses more than adherence and has much more significance for coated materials at high temperatures than at ambient atmospheric conditions.

The interfacial zone has three parts:

1. The outermost surface of the basic metal viewed as a "skin," the significant thickness of which may be from a few angstroms to as much as 0.010 in.;

2. The first layer of the coating which may involve thickness of a few angstroms to as much as 0.002 in., and

3. The alloy formed by diffusion of coating and basic metal which alloy layer can be from a few angstroms to 0.02 in. or more in thickness.

This three-part, interfacial zone and the metallic coating comprise a subject which can be classified as "surface metallurgy".

The contribution of Item 1 to over-all performance is intimately tied in with the history of the basis metal and the <u>kind of operations on its surface</u> (8, 9, 10, 11, 12). Item 2 is considered distinct from the coating proper, because the structure and properties of the initial layers of coating can differ significantly because of interacting effects of influence of the basic metal surface and of properties solely related to the method of applying the coating.

Item 3, diffusion alloy information, will provide the compositions expected according to the phase diagram for the metals involved in the basic metal and coating, but as modified by such effects as time, temperature, and nature of the basic metal surface and of the properties of the coating. The quantitative status of each of the three items will vary somewhat as to need preparation for coating and as to performance in service. Yet, the general effects give guidance for choosing protective coatings, show the areas needing correct technology and excellent workmanship, and give a basis for troubleshooting the causes for poor performance, regardless of the kind of composite system and of method for coating.

<u>Surface Preparation</u>  Prior to actual application of a protective coating, the basic metal surface must be cleaned. Three types of cleanliness are involved. Each affects the integrity of a coating, its adherence, and the bond strength (strength of the intermediate zone).

<u>Physical and Chemical Cleanliness</u>  The importance of these two conditions has long been recognized. Consequently, techniques are well known for removal of oils, greases, and other soils not related to the basic metal so as to provide physical cleanliness. Likewise, pickling, chemical dipping, and blasting methods are well established for removing oxides, scale, and salts that are related to the basic metal so as to make it chemically clean.

**Mechanical Cleanliness.** Too little has been said and done about this important surface condition relative to mechanical properties and to influence on coatings. When mechanical operations are performed on the basic metal the surface is distorted, strained, torn, and smeared. It is important in formation of metal filaments that maximum effort be made to provide uniform surface profile devoid of longitudinal or cross sectional irregularities.

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B.    NONMETALS

Inorganic nonmetallic fibers have been in use since the
days of the Greeks and Romans when the asbestos wick was ignited
as an offering to their gods.  Asbestos is available in nature
in its fibrous form and the natural product requires only physical
treatment to develop a usable fibrous character.  Glass on the
other hand has been in use for many centuries and is today one
of the most common materials found in the home, office, and in
transportation vehicles.  But in its fibrous form, glass is a
relatively new material.  Before 1939 the production of glass
in the United States was valued at less than $4,000,000 while its
use has risen to $200,000,000 in 1955.  With the demand for high
temperature fibers imposed by space requirement, industry has
been plunged into feverish activity in gathering together inform-
ation on inorganic fibrous materials and in developing techniques
for preparing and drawing both old and new materials into fibrous
forms.  Temperature demands which exceed the capacity of normal
types of soda-lime-silica glasses have led to the development
recently of a number of important fibrous refractory materials
capable of maintaining their original properties at temperatures
as high as 2000°F for a prolonged exposure or even up to 3000°F
for short periods.  These fibers include quartz fibers, vitreous
silica fibers and ceramic fibers.  This section will briefly
discuss the properties of the natural asbestos products together
with some recent developments in conventional glasses and finally
the refractory fibers.

1.    Asbestos

Asbestos, a familiar fiber, is being studied more closely
now as a result of the competetive pressure from the new synthetic
inorganic fibers.  A major portion of the current research on
asbestos is carried out at the Asbestos Institute and most of
the information which follows is derived from the work of
Dr. M.C. Shaw at that Institute as reported by Caroselli (1).
Asbestos, a natural product, is available in several varieties.
But 95% of the total world production of natural mineral fibers
is of the chrysotile type of asbestos because of its superiority
in textile processing and its good heat resistance.  The average
strength of such fibers runs about 72,000 pounds per square inch.
Chrysotile is a hydrated silicate of magnesium and maintains its
structure up to about 1500°F.  At this point it converts into
non-fibrous crystalline structure, olivine.  At 750°F a marked
degradation of fiber quality is noted due to the permanent loss

of some water of crystallization. Between 750°F and about 1300°F more of this water crystallization is lost with accompanying loss in strength as shown in Figure 74. Thus it becomes obvious that the effect of prolonged exposure of asbestos to heat is a reduction of tensile strength to a significantly low level. All this takes place below 1300°F

The question of the possible use of asbestos as a high temperature fiber in parachute applications can be answered only when it is determined whether such a fiber can be suitably coated and thermally protected so as to prevent loss of moisture at higher temperatures. Judging from the fact that the fiber is not available in continuous filament form but must be spun of staple fibers which show room-temperature tensile strengths in the order of less than 100,000 pounds, it may be expected that the over-all efficiency of a textile structure made of asbestos will be unsuitable on a strength to weight ratio. It is likely that other inorganic fibers which are under current development will provide a more suitable solution to the parachute problem. Working with a natural fiber which shows as high variability as does asbestos, one may also expect a considerable variation in performance based upon the fiber grade selected and the method of fabrication. Caroselli (1) shows some of Shaw's data which illustrate how fabrics graded by the industry according to the amount of organic fiber blended with the asbestos for ease in processing, cause a wide variation in the percent strength retention at selected temperatures. The Asbestos Institute points out that it can be assumed that asbestos cloths composed of finer cut yarns will exhibit high strength retention charac-teristics. For as a rule, the finer cut yarns contain greater amount of high grade, or long fiber and this factor contributes to greater initial and subsequent retention of tensile strength (2,3).

### 2. Glass

Numerous glass fiber compositions are used in industry today but as Carroll-Porczynski (4) points out, glass fibers in general may be divided into two main groups. The soda-lime-silica groups and the soda-lime-borosilicate glasses. The principal difference between these is the fact that the borosilicate type is alkali free hence more resistant to water and weathering. Water tends to leach the soda out of the body of the soda-lime-silicate glass thus reducing its fiber strength significantly. Five different types of glasses have been adopted to meet various
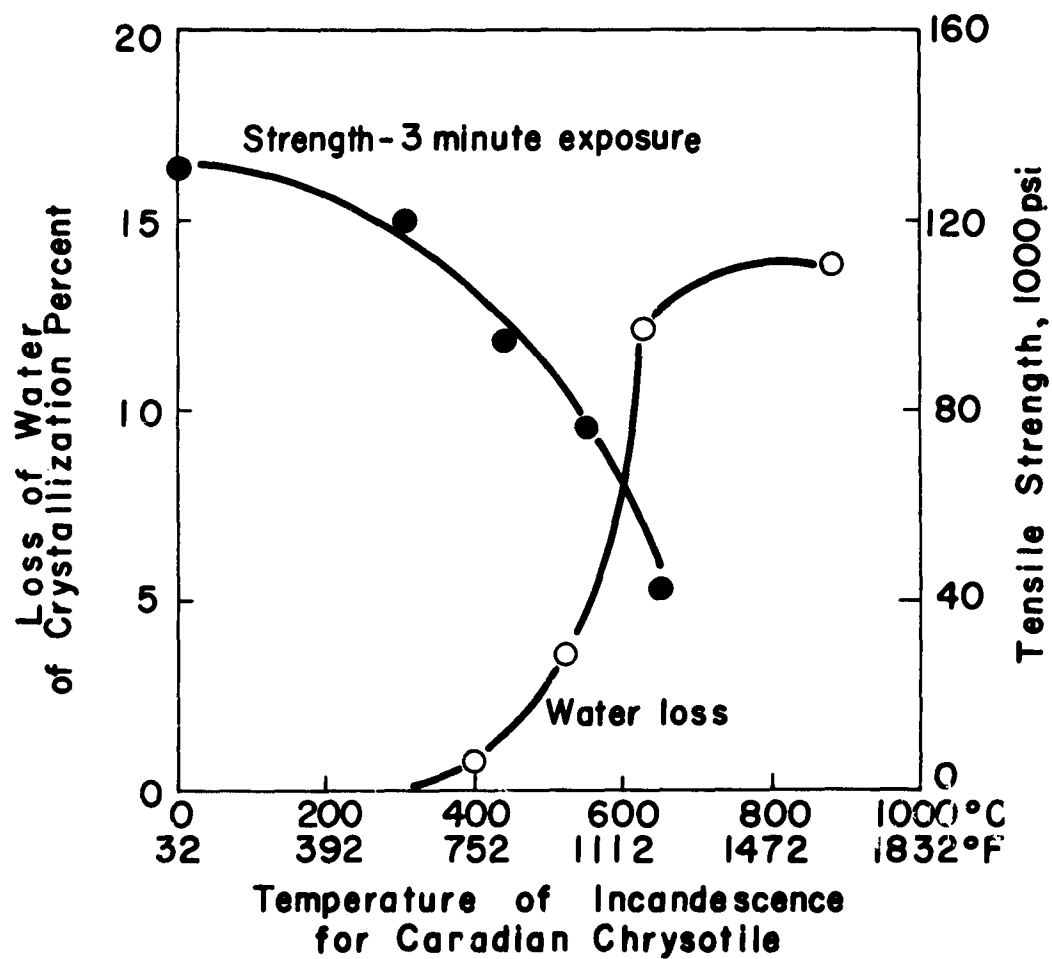
Figure 74. Loss of Water and Strength of Asbestos
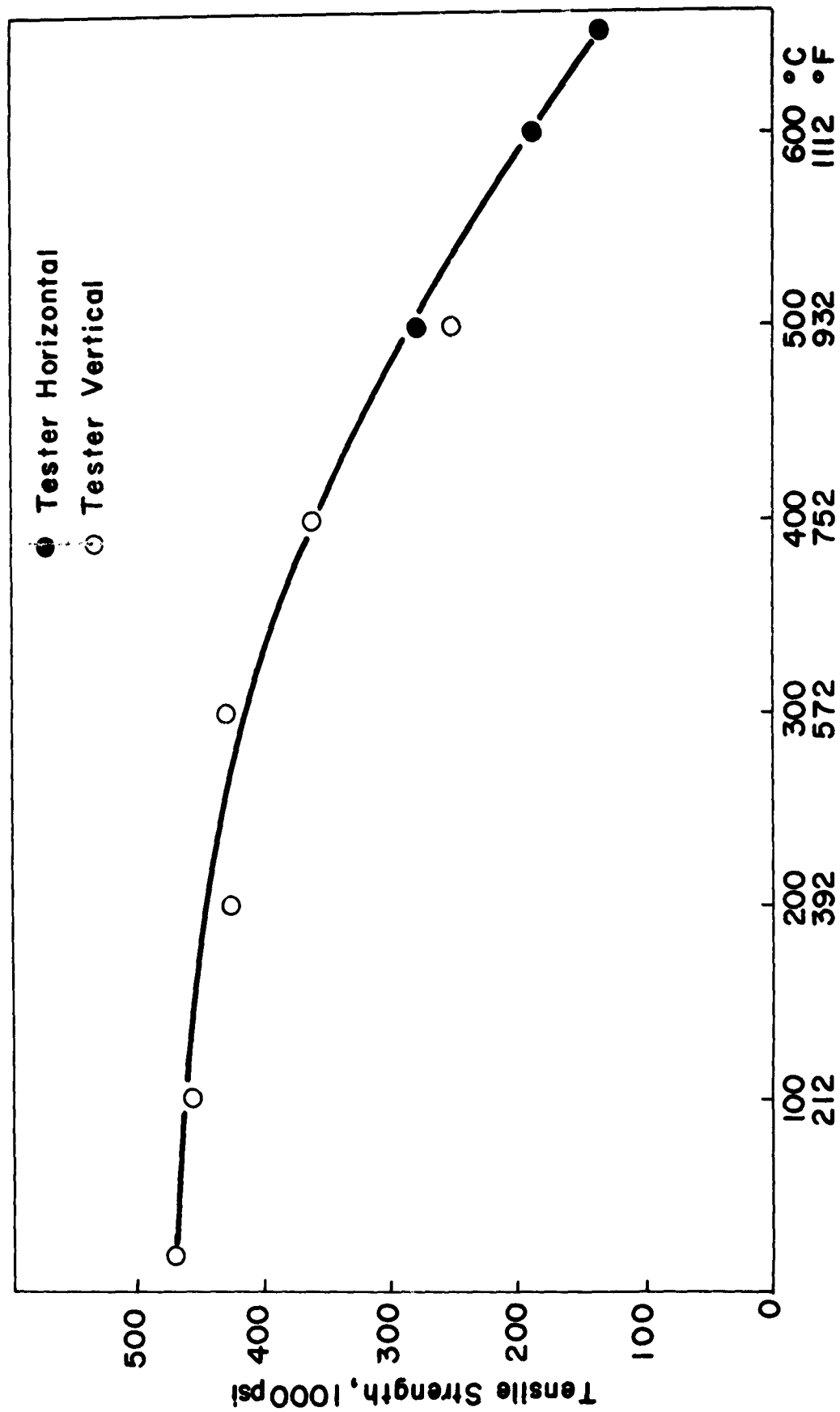
E - Glass  :  Temperature  for  2 Minutes

Figure 75.  Loss in Strength of E-glass Fiber
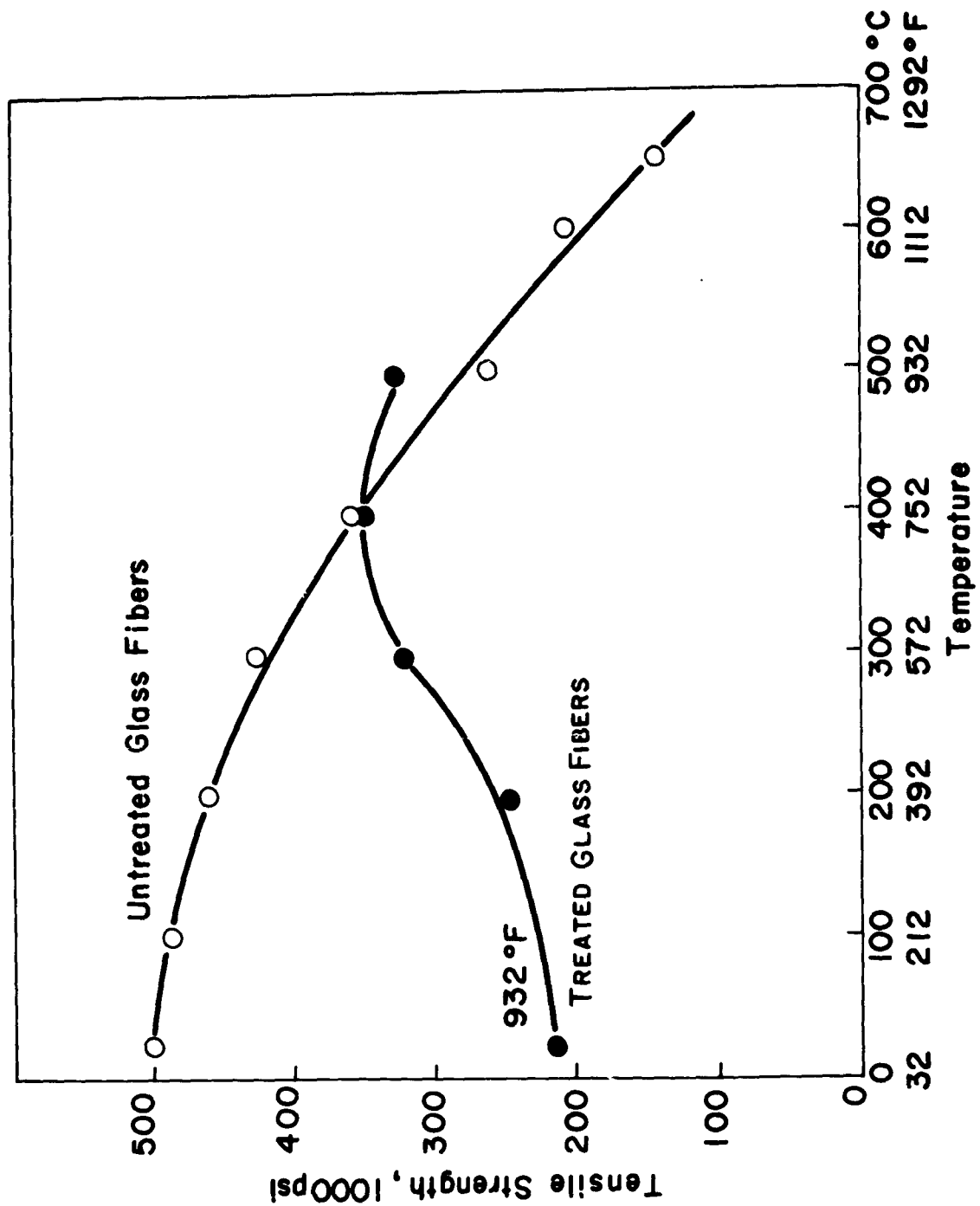
Figure 76. Compaction Effects of Glass Fiber Heating
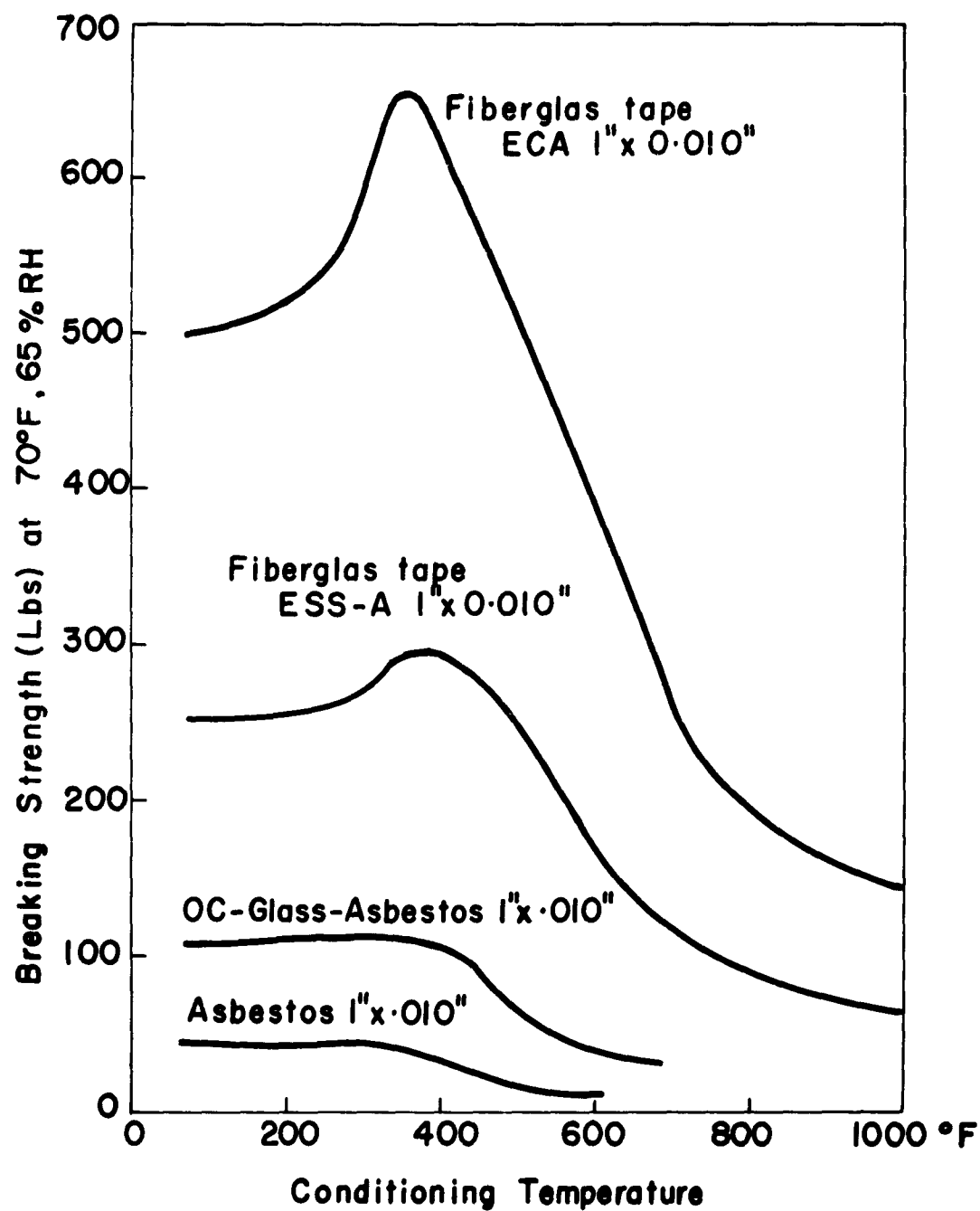
Figure 77. Strength vs. Temperature for Glass and Asbestos Fabrics

requirements of industry. Fiber E, a lime-alumina-borosilicate glass is used for electrical applications and is a soda-lime-silica type of glass of relatively coarse fiber diameter. Fiber T a general purpose borosilica type of glass fiber is produced in a bat form and serves as a thermal insulation. Fiber N is made in form of a superfine wool utilized by the armed services. Fiber C has high resistance to acid and alkalis having been developed for applications such as filter cloth and anode bags.

As a result of the dynamic growth of the glass fiber industry, the technology of spinning and preparing the glass fibers in bat form or in continuous filament form for more conventional textile applications has advanced at a phenomenal rate.

Considerable work has been done on the mechanical properties of type E glass fiber at high temperatures. The tensile strength of E glass fiber decreases from 475,000 psi at room-temperature to 175,000 psi at 1200°F, as pictured in Figure 75. At the same time, Otto points out, pre-heating of fibers causes a compaction and contraction in fiber length and a densification, accompanied by an increase in Youngs modulus. Such compaction or tightening of the glass structure provides increased high temperature strength after heat treatment as shown in Figure 76. The treated glass fiber was held at 932°F for less than an hour. A typical picture of the conversion of fiber strength into fabric strength is pictured in Figure 77 which shows the strength and temperature for glass and asbestos fabrics. All four fabrics are 10 mil thickness tapes: the first a 100% continuous filament glass tape, the second a tape woven of spun glass yarn, the third a combination glass-asbestos tape, and finally an all asbestos tape. In each case the tapes have been exposed to heat from room-temperature to a 1000°F for an hour prior to testing at 70°F. Caroselli(1) points out the superiority of a continuous filament type fabric over the staple types which are so dependent on inter fiber friction and are thus handicapped in terms of internal abrasion.

A modification in glass production has been reported in Great Britain by the British Refrasile Company and in the United States by the H.I. Thompson Fiber Glass Company in Los Angeles. This modified glass fiber has chemical composition similar to that of vitreous silica. In its production, normal types of glasses, in forms of bats or cloth, are leached with acids (other than hydrofluoric or phosphoric acids) so as to extract all of the oxides other than silica. The treatment is carried out at sufficiently

high temperature for a considerable period of time. The fibers washed free of acid, are then heated at an elevated temperature for the purpose of dehydration. The fibers shrink both in diameter and length under this treatment and loose considerable strength with accompanying development of brittleness. Coating of the fiber prior to the leaching process with acid resistant water impervious resin composition minimizes the above effects. This treatment results in a structure of over 96% $SiO_2$ and in some cases up to 99% $SiO_2$. The softening point of these fibers is about 3000°F. The fibers have extremely good resistance to thermal shock. On a practical note, it should be recognized that structures made of these leached glass fibers do not have the tenacity characteristics of ordinary glass yarns. However they are in wide use in high temperature electrical insulation applications in high temperature reinforced plastics, thermo-couple wires, etc. This type of silica fibers is quite usable for a prolonged period at 2000°F and considerable work is now under way to produce leachable glasses with superior strength and even higher temperature resistance.

Another approach to making vitreous silica fibers is that of drawing quartz. Within the last few years production techniques for drawing quartz fibers has been improved tremendously. The Bjorksten Research Laboratories have been successful in producing quartz fibers of indefinite length on a continuous production basis. Strengths up to 600,000 psi has been observed with the average running well over 380,000 psi. Diameters run from 10 microns to 40 microns and the fibers show considerable strength up to a 1000°C.

General Electric has also been active in the field of producing quartz fibers and at present is selling the product on a commercial basis. Monsanto likewise has produced a small tubular fiber of quartz, 3 mils in diameter. It is claimed that this tube is completely flexible and can be knotted with higher tensile strength than steel, while retaining resistance to high temperature (1).

The General Electric product is said to have yarn strength at room temperature averaging over 100,000 psi with very low elongation, amounting to about 3% at maximum stress. In tensile tests at elevated temperatures, the General Electric Company reports that with increasing temperature the strength of quartz yarn decreases. At 1800.F the strength of 200 filament quartz yarns is down to about 15,000 psi. Of course, conventional type E-glass fiber has no strength above 1300°F. The company points

out that quartz like other types of vitreous silica tends to devitrify when held for extended periods of time above the annealing point temperature. Such devitrification causes mechanical failure with the devitrification rate depending on temperature and surface conditions. The density of the amorphous silica is reported as 2.2 g/c.c.

Numerous other companies are experimenting with quartz fibers and we may anticipate comparable improvement in the technology of drawing, preparing the fibers, and fabricating them in textile form. In fact, textile cloths made of quartz yarns are available from a number of sources in the United States at present. Applications of quartz fibers in high temperature parachutes, faces difficulties similar to that of the use of other glass like materials with low extension at rupture, that is the problem of forming the yarn into a suitable fabric and finally the difficulty of stress transfer across points of stress concentration in the parachute. It may be expected that materials of this sort will likewise have extremely poor flex and abrasion resistance and thus necessitate special coating techniques to avoid early breakdown of the structure before it has had time to perform its aerodynamic function.

### 3. Ceramic Fibers

This group is in effect a third group of refractory fibers, the first being the quartz type, the second being the leached glass type leading to a vitreous silica. The third type has its derivation from fiberizing fused natural minerals of an alumina-silica composition, as for example kaolin, bauxite, kyanite, fireclays, etc. The refractory performance of these fibrous materials is of course imparted by the relatively high ratio of alumina to silica (4).

Refractory glass compositions in fibrous forms have been obtained by melting and fiberizing mixures of alumina and silica containing a small amount of borax glass: 50 parts by weight of white alumina ore and 50 parts of weight of flint, are combined with about 1.5 parts by weight of borax glass (sodium-borate). The mixed composition is fused in a special arc furnace until a batch of molten materials results. The material is then poured from the furnace and the falling stream is impacted at right angles with a stream of compressed air. The molten materials is dissipated in the form of fibrous glass. Fiber manufactured in this fashion has been produced by the Carborundum Company and is called Fiberfrax. It is reported that this ceramic type

fiber does not loose its resillience at temperatures as high as 2300°F.

More recently word has been reported by the Carborundum Company (6) in which the melting and firing of refractory glass compositions is described. It is reported that continuous ceramic fibers have been drawn successfully in a dry inert atmosphere glovebox permitting the use of refractory metals graphite and boron nitride as crucible and heater materials, and preventing the absorption of moisture by the filaments. It is reported that several refractory glasses have been successfully drawn in continuous filaments with tensile values of 138,000 psi at room-temperature together with values up to 132,000 psi at 1500°F. While these results are far from representative of a commercial product they nevertheless point to the possibility of developing baria-alumina-silica, calcia-alumina-silica, and magnesia-alumina-silica systems in continuous filament forms suitable for application to extremely high temperature textiles. The next problem which remains of course is to take these high strength, low extension materials and combined them through conventional or unconventional textile processing to form a flexible resillient non-porous textile like sheet.

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# III.    FABRICATION

## A.    INTRODUCTORY REMARKS

Throughout the history of human venture in flight, the parachute has been the principal device for aerodynamic retardation. This key position of the parachute as an air brake has not been altered with man's experimental probing into space nor with emergence of the problem of re-entry into the earth atmosphere.

Parachutes may be made of thin, sheet-like materials such as film, or sheet metal, or conventional textile fabrics. Practical experiences in parachute operation at altitudes well within the earth's atmosphere have shown the advantages of using conventional textile structures consisting of organic fibrous materials. The early candidate material for parachute application was the silk fiber. With the replacement of silk by nylon at the beginning of World War II, the path was opened for investigation of numerous other fibers to be used as substitutes for the unusually strong and tough nylon material. While cotton and rayon fibers had been used quite extensively for other than personnel chutes, nylon remained the principal fiber for the high efficiency drag-to-mass ratio realizable in a parachute structure.

In more recent year, the temperature dependence of nylon's mechanical properties has led to the investigation of other fibers as potential candidates for textile parachute materials (1-5, 9-11). In particular, considerable experimentation has been conducted on Dacron materials (1,10) and in fact some specifications have been established for Dacron parachutes which allow about 50°F. higher operating temperatures than was possible with the nylon parachutes. But nylon still prevails as the principal fiber source for parachute materials.

In considering the properties of inorganic materials studied for high temperature application one concludes that the mechanical behavior of those materials which have appeared to-date to have promising high temperature characteristics, still leaves a great deal to be desired in the fabrication of high strength flexible sheet structures suitable for use in parachute systems. It is likely that the first promising candidate material for high temperature parachute application will be some form of drawn metallic wire. Or if an inorganic non metallic substance is developed, it is likely that its mechanical behavior will be closer to that of

a metallic material than to the viscoelastic behavior of conventional low temperature, high polymer materials. The problem in fabrication becomes a two fold one in dealing with such materials:

1. Fabrication of the material into a thin sheet or a fibrous form, and

2. Fabrication of the sheet or fiber into more complex structural elements of the parachute.

We will concern ourselves here with fabrication from the fiber form into the textile structure which can then be formed into the parachute element. In discussing the individual materials in the previous chapters, we have indicated what success has been developed to-date in fabricating the materials into sheet and wire form. It now remains to cover the final element of chute formation by considering the structure and mechanics of textile designing as it relates to materials with radically different mechanical properties than are normally encounted in the textile industry.

For a suitable parachute material low porosity will undoubtedly be an important requirement and, as has been pointed out, the order of 1% porosity will be desirable. The material should have high strength to weight ratio at the high temperatures of usage. It should have high impact strength. It should demonstrate high translational efficiency of the stress strain characteristics of the fiber into stress strain behavior of the fabric. This means that individual fiber behavior must be realizable to a high degree in yarn and fabric. The fabric structure must be highly flexible. It should have minimum bulk so as to permit packaging in a small volume. Obviously minimum thickness together with maximum flexibility are essentials for minimum packaging bulk. All of these characteristics have been realizable in organic polymer fiber parachute material. The only missing characteristic, of course, has been that of high temperature resistance.

If materials can be drawn into fine wire form suitable for weaving into parachute cloths, it may be expected that the difference between the mechanical behavior of the high temperature fiber candidate and the conventional low temperature organic polymer fibers will be such as to cause considerable variation in the cloth characteristics deemed desirable for parachute application. It is to be expected that difficulties will be encountered in

reaching the desired levels of porosity, strength to weight ratio, impact strength, strength translational efficiency, flexibility, and compactness. Conventional methods of controlling the levels of each of these characteristics in the manufacture of conventional textile fibers will undoubtedly fall short of the requirements when fibers of modified mechanical properties are used. But in order to manipulate the design of the textile structure so as to accomodate in so far as possible the much stiffer, stronger, and more dense high temperature material, it will be necessary to have a full understanding of the governing variables and mechanisms which dictate porosity, impact strength, translational strength efficiency, flexibility, and compactness. The relationships between fabric design variables and the desired characteristics of parachute materials will be discussed in the following sections.

## B.   LOW POROSITY

The Textile Laboratory at WADD has sponsored research on the air permeability of parachute cloth for a number of years. Reports by Lavier (1,22), Goglia (20) and Brown (19) outline the early work in this field and concentrate on studying the laws of flow of air through woven structures. Later reports by Klein et. al. (6, 7) and Seshadri et. al. (8) spend considerable time in discussion and analysis of the structural design of a textile fabric as it relates to air permeability. Note here that "air permeability" refers to the flow of air through a textile structure under a given pressure drop across the fabric, while porosity conveys the concept of relative open space in the projection of the fabric on a plane. The papers by Backer (17) and Perry (15) are devoted exclusively to the effects of geometry on air permeability. Penner (13) also treats the matter of structural geometry of the pore as it relates to fabric permeability. By far the most extensive aerodynamic treatment of the problem is that reported by Hoerner (14). More recent studies in this area have been reported in the general mechanical literature by Tong (16) and Green (24). In practically all cases air permeability of the textile cloth is a function of its structural porosity and we accordingly use the terms interchangeably.

The conclusions of these various researches relative to the important factors which control air permeability of a textile structure are essentially as follows.

The greater the projected area of warp and filling yarns

(taken independently) in a square inch of fabric, the less will be the air permeability of that structure. Where fabrics are fairly open, say in the order of 20% relative projected open area, the permeability of the woven structure will depend to a great extent on both the projected yarn area and the method of interlacing of the fabrics. Where the number of interlacings is high the yarn content at the center plane of the fabric will also be large and a lower permeability will result, than in the case of the fabric which has the same projected warp and filling yarn areas, but with a lesser number of intersections. As the 'projected' porosity of the fabric becomes less and less the tendency of the air permeability to decrease with the number of alternations of warp and filling yarns from face to back of the fabric, continues - provided that in each instance the comparison is made in terms of fabrics which have the same projected warp and filling yarn area. However, when fabrics structures with very low porosities are attempted, it has been shown that the number of yarn alternations present in each square inch of fabric will seriously influence the quantity of yarns which may be packed into a unit area. In other words, if one takes the simplest weave, a plain weave with each warp yarn alternating from face to back of the fabric on each successive pick, the minimum number of yarns may be woven as compared to other structures such as twill or satin weaves. In the case of the twill the warp yarn remains on the face or back of the fabric for more than one cross yarn and thus the number of alternations in each square inch may be drastically reduced. In the satin this tendency is carried still further with perhaps only two alternations of a yarn taking place in five to, say, nine cross-overs of the other set of yarns.

Clearly there is a limiting number of yarns which may be woven for any given pattern and for any given set of yarns. The problem of predicting the maximum weavable structure was treated by Peirce (34) who laid the foundation for the first mathematical treatment of woven fabric structure in its most general context. Later, Love (27) extended Peirce's treatment and provided graphical relationships for plain, twill, and satin weave with a view to predicting the maximum textures of various weaves in terms of their yarn 'cover factors' and the ratio of yarn diameters. Cover factors were defined by Peirce as being proportional to the ratio between the diameter of a yarn and its spacing within the cloth structure. Love showed that as the weave factor (defined as the ratio of the number of threads per repeat of weave to the number of interlacings per repeat of weave) was increased, the maximum textures (yarns per inch) and cover factors weavable also were

increased. For example the maximum cover factor in the plain weave was shown to be 28 while in the three harness weave possessing the weave factor 1.5 the maximum cover factor was 30.2. In the four harness weave with a weave factor of 2.0, the maximum cover factor was 31.4 and in the case of the five harness weave with a weave factor of 2.5 the maximum cover factor was 32.2. It should be recognized that with cover factors exceeding 28 the yarns must either be overlapping one another or in crowding each other under long floats of the opposite system of yarns they compact one against another.

All this structural control is, of course, desirable as a means of reducing fabric porosity. There is however, a limit to which it can be carried, for if one employs weave factors in excess of 2.5 (where float lengths exceed 4 cross yarns) the fabric structure becomes loose and the yarn float may be easily distorted under tensile or sheer stresses within the fabric or under normal pressures resulting from the air flow. The practical proof of the concept of maximum textures as related to weave factors is brought out by Dickson (28) who recites practical loom experience on weavability limits and shows considerable agreement with Love's predictions.

Textile fabrics are composed of yarns which in turn are made up of individual fine filaments or fibers. The yarns are usually twisted together in order to assist in processing of the material or to modify properties of the structure. Where the individual filaments are continuous in length, twist is not essential to create the normal pressures and frictional transfer of longitudinal stresses from one fiber to another, thus in effect, providing the strength necessary for processing of the material and using it in the final structure. Some twist is usually put into yarns made of individual continuous filaments to prevent breaking of individual fibers by rubbing actions or snagging at the surface of the yarn. A slight twist of a ½ to 1 or 2 turns per inch is usually sufficient to furnish the yarn body necessary for efficient processing. If twist in continuous filamentous yarn is increased to higher levels the yarn assumes a hardened structure which maintains its integrity to a higher degree in the woven structure.

The effect of twist in yarns on parachute fabrics has been studied extensively under WADC sponsorship by Chu et. al. (32). He arrived at over five general conclusions concerning the effect of twist on yarn in parachute fabric as follows:

> 1. "The flow of air through the open areas of a fabric obeys the general rules of fluid mechanics namely: flow at any given pressure differential varies with

the amount of open area; and the rate of flow at
varying pressure differentials follows the square root
of the pressure differentials with suitable modifying
constants to allow for those changes in the open area
which occur when the fabric is subjected to biaxial
extension exerted by the air pressure."

2. "The free area available for air flow varies as a
function of fabric and yarn geometry. The ellipticity
of the yarn cross section is functional with the yarn
twist; flatter the yarn, the less is the open space
between adjacent yarns. Hence for a given texture the
free area varies inversely with the yarn width.

3. "The open areas change when the fabric under test
is subjected to increased pressure differentials. The
yarn systems in the fabric structure, when so stressed,
result in biaxial extensions which widen the space
between the yarns. The rate at which the open areas
vary with pressure differential may be determined by
studying the fabrics' biaxial stress-strain behavior.
At the present writing only limited studies have been
made."

4. "The magnitude of open areas in any fabric may be
calculated from the yarn width determined microsco-
pically and the fabric texture. However, a more
precise method has been developed by measuring light
penetrability through the use of a Beckman Spectro-
photometer."

5. "In general the following trends have been shown to
be evident:  with the increase of yarn twist

| | |
|---|---|
| Fabric thickness | Increased |
| Denier of yarn removed from fabric | Increased |
| Horizontal yarn diameter | Decreased |
| Vertical yarn diameter | Increased |
| Free area: area between yarns | Increased |
| Light penetrability | Increased |
| Air permeability | Increased |
| Freedom of yarn slippage | Increased |
| Yarn tensile strength | Increased |
| Yarn elongation | Increased |
| Energy to rupture yarn | Increased |

| Strip tensile strength | No visible change |
| Fabric elongation | No visible change |
| Secondary creep | Increased |
| Tear strength | Decreased |
| Tear energy | Decreased |

It would be interesting to have data on the fabrics studied by Chu relating bending rigidity and weavability of the parachute fabric to the twist in the yarns. Increased twists obviously improved the cross sectional integrity of the individual yarn, thus reducing its flattening tendency. This flattening is observed to contribute significantly to the reduction in porosity for a given fabric texture (yarns/inch). However, an increased twist frequently reduces the bending rigidity of the yarn as shown by Platt et. al. (29). Although Love (27) did not consider the effect of bending rigidity upon the weavability of fabrics structure it is clear that in order to accomodate two ortho-gonal sets of yarns at the same central fabric plane, a good deal of yarn bending takes place in the weaving process. It is quite possible that an increase in yarn twist may reduce the flattening factor in individual yarns and thus increase the fabric porosity for a given texture. However, the same increase of twist may increase the flexibility of the yarn to such an extent as to allow for higher practical weaving limits. It should be clear that the effect of twist is not a univalued effect as it relates to porosity in conventional textile structures. Its influence in structures woven of wire or other high modulus material will have to be investigated to permit exploitation of this variable in achieving minimum parachute fabric porosity.

This discussion of the effect of yarn twist on parachute fabric properties would not be complete without emphasis on the effect of twist relative to mechanical behavior of the fabric. We note the increase in textile strength reported by Chu et. al. (32) as twist went up, but also we note the reduction in tear strength of the fabric with a higher twist. These accompanying twist effects will be discussed in the following sections, but for the time we would like to consider the additional effects of twist on the porosity of woven structures. Here we refer to the interaction between the twist direction in a woven structure and the weave pattern, or weave geometry. It has been observed by Backer et. al. (30) that the path of a yarn in a woven structure does not consist of simple vertical oscillations of the yarn in a plane perpendicular to the fabric, in the so-called crimp plane. Rather there is a movement of the yarn laterally within the plane of the weave. This lateral movement accompanied by the vertical movement of the yarn as it progresses along the fabric may affect the local geometry in the yarn and therefore

its local mechanical properties. It likewise may affect pore size and shape in the fabric structure. Thus in some fabrics it may be observed that some pores are larger than others even though the fabric has been woven with equal spacing between yarns and with yarns of uniform size. Such systematic inequalities between pores have been shown to result from systematic shifting of the yarn as it progresses through the fabric so that all upper right hand and lower left hand pores may be large while the opposite number pores may be small due to rotation of local segments of the yarn in the plane of the fabric, (See Seshadri, et. al., 8). This type of shifting which takes place in a fabric with a symmetric weave (that is, where the weave is symmetric to the left and right of a given yarn) may be attributed to the torsional instability of the yarn and its tendency to buckle in a direction matching that of the direction of its original twist (30). Usually such segmental rotation and local buckling occurs in fabrics which are of open structure and constructed of yarns with fairly high twist. The concept of local buckling is carried to an extreme in the very high twist open structure cotton fabrics which are used as elastic bandages without rubber.

Frequently torsional buckling of the yarn in a fabric structure is motivated by non-symmetric lateral pressures of the fabric weave. This would be typical of the influence on yarn geometry of a twill or satin weave, such as may be used to acquire maximum cover factors during weaving (27) (30). One might reason that the lateral buckling of the yarn in a fabric structure will not only influence the pore sizes, but also influence the local twist of the yarns which have buckled, as it has been shown the effect on pore size and shape is real (8), whereas the effect of local loosening of yarn twist during lateral buckling on fabric permeability is obscure (30).

One must conclude that techniques for obtaining low permeability in textile structures cannot be overlooked in the preparation of high modulus fibrous materials. The likely increase in yarn stiffness of such materials will undoubtedly necessitate the use of looser weaves, that is structures with higher weave factors. High effective cover factors in such structures can then be achieved through use of overriding and lateral crowding of one set of yarns, preferably the warp set.

One should not exclude the possibility of introducing (through a calendaring operation after weaving) a highly stable organic film or fiber covering which will effectively block

the remaining pores centrally located within the fabric structure. A hot nitrogen treated orlon has been mentioned as possessing thermalstability at Bunsen burner temperatures (33). A material of this sort could also be coated on the individual metal filament before weaving and subsequently calendared and heat treated, as a means of providing pore blockage and minimum porosity for the woven structure. Existence of such a film or pore blocking within the fabric structure would undoubtedly increase its thickness and would increase the danger of formation of severe creases in the cloth during packaging and storage. The effect of fiber properties and fabric structures on packaging and unfolding characteristics will be considered as a separate item, but it should be obvious that treatments and designs intended to reduce porosity will in most cases influence adversely the flexibility and packageability of the high temperature textile structure. This has been shown to be the case in the application of coatings to textile fabric (38), where the coating serves to block the pore between the yarns and thus reduce crimp interchange and yarn slippage so necessary to accomodate the fabric to application of stresses at a local point.

C.    HIGH STRENGTH TO WEIGHT RATIO

Parachute materials must be capable of withstanding high stresses and at the same time should have minimum weight. It is therefore customary to judge the potentiality of new engineering materials for parachutes in terms of their strength to weight ratio. This ratio is determined by dividing the breaking strength or unit stress at a given offset by the specific weight of the material. The dimensions of such a ratio will be length to the plus one power. A similar measure of conventional textile fiber properties is termed 'tenacity' and is obtained by dividing the breaking strength (load) by the fiber fineness (denier or grex expressed in gms/meters). The ratio dimension is likewise length to the plus one power. This length unit has the physical significance of breaking length, that is, the length of material which will of its own weight just cause breakage of the yarn or cord under consideration. The following table furnished by Smith (36) illustrates the relative differences between typical textile materials and structural steel with regard to tensile stress (in $lb/in^2$) and tenacity (in gms/grex), the equivalent of specific strength or strength/weight ratio for the materials concerned. It is observed that while steel exhibits a higher tensile stress than most textile fibers, in terms of tenacity or specific

strength it is one of the lowest. Glass fiber (undoubtedly tested under a very exacting condition) shows up as having both the maximum tensile stress and the maximum tenacity. There is little experience to speak of in the use of glass fabrics for parachute application. The stiffness of glass and that of steel when based on unit weight are about the same, ranging from 5 to 10 that of the specific stiffness of nylon or dacron. This suggests considerable difficulty in adapting either glass type or steel type fibers to parachute cloth and parachute applications.

Strength/weight ratio and specific stiffness do not constitute all the important mechanical behavior characteristics of textile fibers. Fibers used in conventional fabrics are viscoelastic, demonstrating three forms of extensibility: 1) that which is recoverable on an immediate 'elastic' basis, 2) that which is recoverable after some delay, and 3) that which is considered as 'permanent set' is recoverable under the conditions of test. These extension components suggest that the textile fiber may be formed into a woven structure and then set so as to reduce internal stresses in the system. Fibers vary in their recovery components at different levels of extension. The following table is indicative of the tensile behavior and elongation components of a number of filaments tested by Susich et. al. (35). It is noted that the two fibers which have been used extensively for parachute application, namely nylon and dacron show breaking elongations between 18% and 23% in the form used (methods of drawing and heat treatments of these fibers can modify their mechanical properties to a major degree). Cotton and viscose have also been used for parachute applications, however, more in connection with cargo chutes than personnel chutes. They still work as suitable textile materials for parachutes with elongations at break ranging from 5 to 16%. The breaking tenacities of cotton and viscose range from 1.5 to 2.5 while the dacron and nylon texted range from 5 to 6 gms/grex. Silk, the fiber used for parachutes in the past, showed a breaking tenacity of about 4.4 and a breaking elongation at 20%.

At 50% of breaking tenacity the conventional silk showed 47% of its extension was elastic. Nylon Type 300 had 29% elastic recovery, Dacron 33%, Viscose 28%, while cotton showed 63%. It should be noted that values of breaking tenacity are based upon original linear density or original cross sectional measurements of the fiber, and are not adjusted for reductions in diameter which may occur as a result of the applied stress. In considering the metals which may be used in fine filament form it is anticipated

that their immediate elastic recovery at 50% of breaking tenacity will be far in excess of any of the values shown for these fibers which have been used successfully in parachute applications in the past. On the other hand, total elongation at break will be far lower in the case of metal fibers than for any of the fibers which have been evaluated in this table with the possible exception of fiberglas, breaking at about 2.3% extension. The metal fibers as in the case of fiberglas will undoubtedly show up as a much higher elastic material with greater rigidity (note the 78% elastic recovery for fiberglas at 50% of its breaking tenacity).

It is clear that the wide divergence in density from nylon at 1.15 to the high temperature materials considered in this report and in particular to metals such as steel at 7.8. This suggests that considerable juggling will have to be done in terms of fabric weight, fiber sizes, etc., to permit design of a parachute with satisfactory strength, satisfactory weight, and satisfactory cover power (leading to acceptable low porosities).

Tensile strength is by no means the principal mechanical factor related to the successful deployment of a sheet material in a parachute. Both breaking tenacity and total elongation at break must be accounted for, as it has been suggested by Smith and the product of these two (or one half the product) may be used to approximate the area under the stress-strain curve and thus the toughness or work to rupture of the material. In such calculation it is seen that the nylon specimens are, by far, most desirable, while glass which has the highest tenacity is poor in this respect of toughness. Fortisan on the other hand, which shows a maximum tenacity of 6.7 and a total elongation of 5.8 is still far below the nylon. Fortisan however, has found some use in parachute application.

These fibers are not discussed with the idea that any of them may be useful in very high temperature parachute application, with the possible exception of fiberglas in some of its modified forms. The point to be stressed is that fibers which vary tremendously in their mechanical properties have been used in suitable parachute structures. These fibers likewise vary considerably in cross sectional area and shape. The data suggests that the parachute fabric designer working with high temperature materials possessing lower extensions and higher tenacity will have a fair number of variables which he may manipulate in achieving the desired structure. The one final point to be made this time is that when one discusses high strength/weight ratios for the materials under consideration, these ratios must be determined

## TABLE 8 - AIR-DRY STRENGTH OF SOME FIBER MATERIALS

| Material | Density | Tenacity g per gx | Tensile Stress psi. | |
|----------|---------|-------------------|---------|---|
| Nylon | 1.14 | 4.0 to 6.3 | 55,000 to | 102,000 |
| Silk (boiled-off) | 1.35 | 2.2 to 4.6 | 42,000 to | 88,000 |
| Wool | 1.32 | 1.1 to 1.5 | 21,000 to | 28,000 |
| Acetate rayon | 1.32 | 1.2 to 1.5 | 22,000 to | 28,000 |
| Vinyl fibers | 1.35 | 1.8 to 3.6 | 35,000 to | 69,000 |
| Hemp | 1.49 | 5.3 to 6.2 | 112,000 to | 132,000 |
| Jute | 1.49 | 2.7 to 5.3 | 57,000 to | 112,000 |
| Flax | 1.50 | 2.4 to 7.0 | 50,000 to | 150,000 |
| Viscose rayon | 1.52 | 1.8 to 4.5 | 39,000 to | 97,000 |
| Saponfied acetate rayon | 1.52 | 4.5 to 6.3 | 97,000 to | 136,000 |
| Cotton | 1.54 | 2.0 to 5.0 | 44,000 to | 109,000 |
| Vinylidene fibers | 1.72 | 3.6 to 5.4 | 88,000 to | 132,000 |
| Glass | 2.54 | 6 to 30 | 217,000 to | 1,100,000 |
| Steel (structural) | 7.8 | 0.4 to 1.1 | 50,000 to | 125,000 |

## TABLE 9 - DATA OF TENSILE PROPERTIES AND ELONGATION COMPONENTS OF SELECTED FIBERS

| Material | Characteristic and Designation | Actual Fineness (grex) | Breaking Tenacity (g/gx) | Total Elongation at Break % | Elongation Components in Per Cent of Actual Total Elongation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | At 50% of Breaking Tenacity | | | At the Breaking Point | | |
| | | | | | Immed. Elastic Recovery | Delay-ed Recovery | Perma-nent Set | Immed. Elastic Recovery | Delay-ed Recovery | Perma-nent set |
| Fiberglas | Multifilament 900-1/2 | 114 | 5.81 | 2.3 | 78 | 19 | 3 | 72 | 22 | 6 |
| Cotton | Staple Yarn 50/1 | 118 | 1.56 | 4.6 | 63 | 35 | 2 | 44 | 32 | 24 |
| High Ten. Fortisan | Multifilament 90/120/3 | 100 | 6.68 | 5.8 | 50 | 34 | 16 | 44 | 28 | 28 |
| Saran | Monofilament 5 mils diam. | 200 | 2.32 | 13.4 | 53 | 47 | 0 | 42 | 58 | 0 |
| Regular Viscose | Multifilament 100/40 | 111 | 1.83 | 14.7 | 50 | 42 | 8 | 19 | 20 | 61 |
| High Ten. Viscose | Multifilament 100/40 | 111 | 2.51 | 15.8 | 28 | 38 | 34 | 18 | 21 | 61 |
| Orlon | Multifilament 100/40/z | 111 | 4.19 | 16.6 | 30 | 47 | 23 | 21 | 37 | 42 |
| Dacron | Multifilament 100/48 | 111 | 5.17 | 18.2 | 33 | 52 | 15 | 18 | 37 | 45 |
| Silk | Multifilament 100/132 | 117 | 4.39 | 19.0 | 47 | 42 | 11 | 16 | 20 | 64 |
| Acetate | Multifilament 100/40/2.5 | 111 | 1.23 | 20.5 | 74 | 26 | 0 | 14 | 16 | 70 |
| Nylon Type 300 | Multifilament 100/40/2.5s | 111 | 5.52 | 23.3 | 29 | 67 | 4 | 18 | 54 | 28 |
| Vinyon | Multifilament 100/50 | 111 | 2.65 | 31.1 | 17 | 39 | 44 | 12 | 28 | 60 |
| Wool | Worsted S.Yarn 234/1 | 314 | 0.81 | 31.9 | 64 | 34 | 2 | 16 | 44 | 40 |
| Casein, Stabilized | 398/40 | 333 | 0.83 | 40.8 | 77 | 23 | 0 | 12 | 28 | 60 |
| Polyethylene Type 2 | Monofilament 12 mils diam. | 664 | 1.17 | 41.3 | 76 | 24 | 0 | 10 | 30 | 60 |

at the temperatures which it is expected the parachute material will encounter, presumably about 1500°F.

## D. FACTORS INFLUENCING STRUCTURAL EFFICIENCY OF TEXTILES

The fibrous forms of many substances are observed to have extremely high tenacities. In some instances technical strengths approaching theoretical limits have been obtained in fiber materials. Varying reasons account for this unusual strength. Absence of macro and micro cracks are considered to be the reason for the high strength of freshly drawn glass filaments. Elimination of crystal discontinuities or dislocations explains the high strength of metal "whiskers". High crystallinity and orientation are attributes contributing to high tenacity and high modulus of finely drawn organic textile fibers.

The fibrous reinforcement in plant leaf, stem and trunk and even in animal body tissue is nature's method of forming a relatively soft flexible system endowed with moderately high extensibility and at the same time capable of supporting heavy loads. The inherent slenderness ratio of the fibrous reinforcing elements of such systems provides the structure with a low bending rigidity despite the fiber modulus of elasticity in tension or in shear. Such flexibility is, of course, increased if the matrix surrounding the fibers has very low shear rigidity and/or readily permits relative movement between fibers during bending of the structure. The ultimate in structural flexibility is achieved when the fibers of a structure are not embedded at all, and when the coefficient of friction between the fibers is minimized.

The flexibility considered so necessary in textile structures is accompanied, unfortunately, by a considerable loss of efficiency of translation of the extremely high fiber strengths into yarn and fabric strengths. Further, there is a loss in fabric strength potential in the fabrication of end items via the sewing process. This inability to translate fiber tenacities into yarn and fabric strength is sometimes due to the inherent weakness of the fiber, to local shear stresses and to lateral normal pressures - as in the case of glass fibers. But in the main, structural strength inefficiencies of textile systems are due to the overwhelming strain inhomogeneities forced on the average yarn or cloth specimen in daily usage.

The twist or the helix angle of fiber in the yarn determines the stress and strain level for each fiber at different yarn strain levels. The crimp inclination angles at load equilibrium determine the local stress level for yarn in a fabric subjected to uniaxial

tension or biaxial tension. The degree of yarn flattening likewise influences the local strains in the yarn crown in the stressed fabric. And in bending of fabrics the local twist, the orientation of warp and filling and the mobility of fibers within the yarn and fabric structure all influence the local strain level. Finally, at the joining between fabrics the type of seam, the stitch length and the mobility of yarns in the joined fabrics interact to establish a pattern of local strains.

Where a high degree of strain inhomogeneity is the order of the day the stress-strain characteristics of the fibers interact with the structural geometry of the fiber assemblage to determine strength efficiency of the system. Maximum strength efficiency can be defined as the case where the fibers working together in the system give rise to a load bearing capacity equal to the sum of the tensile strengths of the individual fibers tested separately.

The textile structure subjected to a non-homogeneous strain will fail in a stepwise fashion with the failure initiating where the local strain first exceeds the strain to rupture of the fiber present at the point. The failure may propagate from this position leading to early failure of the entire structure. But it is also possible for other regions of the material to reach breaking strains before the initial failure in the system propagates catastrophically to a complete rupture.

Knowledge of the strain inhomogeneity can be used as a basis for calculating the stress distribution in a given structure, as well as the integrated contribution of this stress to tensile resistance in a given direction. The case of twisted yarns has been treated in this way by Platt (TRJ - 1952) (44); the non-woven structure has been studied by Petterson (M.I.T. - unpublished) (41). The experimental confirmations of Platt's and Petterson's analyses were restricted to uniaxial strain. However, Petterson's non-woven fabric analysis affords predictions of general plane stress-strain behavior. While Petterson's experiments did not include biaxial stress, no doubt experiments can be devised to reproduce more complex stress and strain conditions for the non-woven.

The analytical treatment of yarn and non-woven fabric uniaxial strength illustrates the importance of fiber stress-strain properties in the realization of high strength efficiencies. The stress-strain curve which portrays a flat region in the vicinity of rupture assures maximum contribution of fiber strength to fabric

strength. This follows from the fact that those fibers which have not quite been strained to break in the system at the time of the initiation of rupture (at a single point of the material) will likely be strained up into the flat region of their stress-strain curve and will contribute the major share of their strength at that moment. If their stress-strain curves lacked the broad flat region at rupture then the presence of strain differentials in the system would find many fibers contributing but a small part of their strength potential at the time of failure initiation. Platt has characterized this flat section of the stress-strain curve in terms of its slope and intercept. Clearly a small slope and a large intercept are desirable elements for high strength and strength efficiency in a fibrous structure.

Uniformity in strain to rupture is another extremely important characteristic of the individual fiber in determining its strength transfer efficiency. For if certain fibers in a population have extremely low values of rupture strain, they will fail at an early stage in a strain field which may in itself be fairly homogeneous. And this failure may lead to successive rapid failures of contiguous elements. Actually, the placement of fibers with widely varying rupture strains in a relatively uniform strain field is similar to placement of uniform propertied fibers in a non-homogeneous field. The parameter which Platt (TRJ - 1950) (40) suggests as most indicative of the fiber's uniformity contribution to strength efficiency is the coefficient of variation of fiber elongation to rupture. And this coefficient has been used effectively in analytical treatment of the uniaxial strength of yarns (TRJ - 1952) (44). Of course, other aspects of non-uniformity play an important part in determining fiber strength contribution. For example, the presence of weak spots in the yarn will influence yarn strength, the effect being a function of gage length (Peirce J.T.I. - 1926) (45). Similarly the uniformity or lack of uniformity of cross-section will influence the ultimate stress-strain curve of the fiber (Kenny and Chaikin J.T.I. 1959) (46) and that of the yarn (Backer - M.I.T. unpublished) (47).

These studies of the influence of non-uniformity of fiber properties point the way to numerous other areas of investigation related to the question of strength efficiencies in textiles. For example, the case of parallel fibers considered by Platt can be extended to the treatment of yarns in loose open fabric. The weakest link theory of Peirce can be applied to non-wovens (Petterson - M.I.T. unpublished) (41) and to textile components subjected to series loading in general. Both approaches are useful in the case of the stressed seam which contains elements of parallel and of series loading.

In the treatment of more complex structures one must account for the presence of complex stresses. The single yarn in a close woven fabric can no longer be considered as independent of its neighbor. If the single yarn varies along its length in cross-section, packing factor, or tensile modulus, it is no longer free to obey the simple rules of series loading, i.e. local strain being inversely proportional to local stiffness. For the local strain in the yarn must be consistent with that in the contiguous yarn as determined by the cross thread coupling. The importance of the coupling is dependent on properties of the cross thread, and in particular on the mobility of yarn in fabric.

Failure in a closely woven fabric is likewise influenced by the presence of threads laid perpendicular to the principal direction of tension. If the longitudinal threads are completely uniform in cross-section and in modulus along their length, the first break will occur in the yarn possessing the lowest extension (as tested singly and uniaxially). It is questionable, however, whether the next break will take place in the yarn which has the next lowest extensibility. For as the first yarn ruptures and seeks to discharge its strainenergy it is prevented from freely doing so by the cross yarns which pick up part of the tensile component necessary to maintain the extension of the first yarn. This tensile component is transferred (as the cross yarns rotate) to the contiguous longitudinal yarns with the major concentration of stress located at the area of initial rupture. The ability of the contiguous yarn to support the added stress will of course determine whether the break will propagate or whether the system can assume additional overall extensions leading to failure of the second least extensible longitudinal yarn. The level of stress transfer from one broken yarn to another is dependent on the closeness of weave and frictional resistance of the surrounding matrix, the properties of the cross yarn, and the extensibility of the contiguous yarn. Clearly if the cross yarn has a low modulus and a high rupture strain it can extend sufficiently to accommodate the withdrawal of the broken yarn and permit its discharge of strain energy. On the other hand if the adjacent yarn has a high modulus and a high breaking strength it can likewise accommodate the effects of the nearby failure, this time by shouldering the extra load necessary to keep the ruptured yarn in its extended configuration.

In most instances the occurrence of a failure of a single yarn in a woven fabric leads to early rupture of the entire system and there is little evidence of simultaneous propagation of several nuclei of rupture. But most observations which lead to this

statement are for the most part based on "slow test" histories and little is known of the phenomena of impact failure of woven, knitted, or braided structures. It is true that every rupture phenomenon in a highly extensible, strong, fibrous system occurs in extremely short intervals and can be classified as propagating under "impact" conditions. But it is equally true that rapid imposition (as contrasted to slow test rates) of the events leading to the initial rupture will strongly influence the mechanical state of the fibers and geometric state of the yarn and fabric at the first moment of failure. This mechanical state will determine the nature of the rupture propagation in the fabric.

The questions of importance are: "what is the true geometric configuration of the fabric at the moment of rupture initiation and what are the factors which influence this configuration." Information on the true geometric configuration of a textile system can be obtained from surface photographs and in the case of impact tests these photographs must be taken with high-speed camera or flash lighting equipment. But the vital information which will form a basis for calculating strength efficiencies in advance, cannot be obtained from surface photographs-- any more than the structural design of a building can be evaluated from an aerial photograph.

Internal displacements and strains of the fabric components must be measured before an intelligent analysis of stress concentrations and overall strength efficiency can be undertaken. Clearly the "internal" view of the structure cannot be obtained except by a sectioning process. Sectioning of a fibrous system for microscopic view generally implies an embedment, successful techniques for which have been developed many years ago. While the early embedding methods have been restricted to unstressed yarns and fabrics, progress has been made in the last ten years in developing the "stress-embedding" process which fills the cited need under static conditions of loading. But the problem remains to develop a system of instantaneously freezing the internal configuration of the impact loaded textile component, and this is not a simple task.

Alternate approaches to the problem of determining structural configuration of textile assemblages could involve simulation of the variation in certain factors which are influenced by overall strain rates. We recognize fiber stress-strain behavior and inter-fiber friction as important factors which influence geometric response of a particular fabric structure to a given load. The factors vary with strain rate in a known manner. They can be made to vary in a similar manner with temperature or with surface finish.

Thus by altering temperature and or surface finish one can approximate the response of these particular factors at relatively slow strain rates. A further approximation can be made by fixing the boundary strains of the sample for a given load then embedding via the newly developed "stress-embedding" technique. Sectioning of specimens prepared in this fashion should provide some indication of differences in geometric response to be expected in impact versus static tests, although the breadth of the assumptions underlying this experimental approach make quantitative predictions in this area highly suspect.

The fabricator of a parachute made from a glass-like fiber or from a high temperature metal may consider the above comments (48) on structural efficiency of textiles to be too general for direct application to his design problems and so a more detailed treatment of the problem is warranted.

A major item of concern to the designer of a wire parachute fabric is the influence of twist in the yarn upon the structural efficiency of the woven fabric. The effect of yarn twist on yarn strength has been studied by textile technologists extensively in the last 25 years. At an early stage of these studies it was observed that more general relationships between strength and twist could be obtained if twist were expressed in terms of a twist multiple. The 'twist multiple' is directly related to the outside helix angle of the twisted structure (also to the product of twist and radius of the yarn) and therefore it is a more basic geometric quantity than is 'twist', expressed in terms of term/inch. Thus one can find (for a variety of fibers) all sorts of strength or tenacity vs. twist multiple curves cited in literature. Truslow's Handbook of Twisting (49) contains a series of these relationships for most of the conventional fibers used in the textile industry.

In general strength utilization or strength efficiency curves vs. twist multiple have a parabolic shape. The form of the relationship is usually as follows. The strength of the twisted structure is equal to the strength of the untwisted filaments minus the product of a constant, the square of the twist, and the square of the yarn radius. The constant determines the geometric effect on yarn strength. This constant is directly related to the stiffness of the fiber at high loads and to the strength of the fiber. The higher the fiber strength and the softer its stress-strain curves at high loads, the less would be the geometric effect. Truslow cites data from Platt and Taylor showing how

viscose fibers, glass fibers, Orlon fibers, Dacron fibers, nylon fibers, and acetate rayon behave in single twisted yarns. In general it is found that the low tenacity, high elongation form of any fiber provide a strength vs. twist curve which has a considerable flat portion and which does not fall off to rapidly at higher twists. Higher tenacity forms of viscose and of nylon, for example, show a lower order of strength utilization and a more rapid drop off in strength with higher twist (40, 44, 49, 50).

One factor not explained by the purely geometric studies which have treated the relationship between strength and twist is the tendency for yarns to increase somewhat in strength at relatively low twist as compared to zero twist strength. This slight increase in strength can be attributed to the fact that in the zero twist yarn some fiber paths and fiber lengths (even in a filament yarn structure) are of different length than the average gage length in the test. As a result, those fibers with longer paths and shorter lengths will be subjected to higher tension than those with shorter paths in the original structure. The slight twist added to the yarn structure causes the fibers to migrate back and forth from the center to the outside of the yarn to the extent that excessive fiber length now follows the longer paths in the yarn structure, while the shorter fiber lengths have the tendency to migrate to the paths of least length, (those with minimum helix angle) at the center of the yarn. In effect the low twists of one or two twist multiples reshuffles the fibers and takes up the slack. As a result, in stressing a low twist filament yarn one is often assured of better distribution of stresses among all fibers of the yarn structure.

Generally speaking the twist of a yarn structure determines the helix angle of the individual fibers in a more or less systematic pattern. If the yarn is subjected to a tension between fixed gage lengths, each fiber will react to that tension in accordance with its position within the yarn. Those fibers which have high helix angles will experience a strain equal to the strain of the gage length yarn times the cosine squared of the helix angle. In turn, the stress contributed by a yarn at a given helix angle is equal to the stress in the fiber developed from the fiber strain times the cosine squared of the helix angle. Thus we have a double multiplication involving a cosine and in general the contribution of an initially unstressed fiber to yarn structural efficiency is related to the forth power of the cosine of its helix angle. This relationship as pointed out can be disturbed if the fiber in its original geometric configuration

is not relaxed or has excess length beyond that called for the helical path corresponding with its helix angle. The procedure for analyzing the behavior of this structure in a straight configuration is outlined by Platt (40) and consists of determining local strain for individual fibers, local stresses for those fibers, and then a contribution to the stress bearing ability of the yarn along the yarn axis. The result is the parabolic form of the strength vs. twist relationship cited above.

The behavior of ply yarns in a strength vs. twist study is not unlike that of the single yarns. Truslow (49) suggests that formulations for ply yarns strength are the same as those for single yarns except that the primary helix angle to be used is that between the outer fibers and the axis of the individual ply. In the usual manufacturing procedure the single's twist direction is reversed in the ply structure and thus a major portion of the singles yarn twist is removed during plying. If the helix angle of the outside fibers is such that these fibers lie essentially parallel to the axis of the ply yarn, the structure is termed 'balanced'. When one measures the 'reduced local helix angle' between the outside fibers of the single yarns and the axis of the singles yarn as it lies in the ply, one can then calculate the potential strength of the singles. This singles strength is then multiplied by the number of single yarns in the ply structure and by the cosine of the helix angle of the ply to give the total strength potential of the ply yarn. Obviously if the local helix angle in the single yarns can be reduced to zero as a result of the reverse twisting during the plying operation, the strength efficiency of a structure should be quite high, limited geometrically only by the cosine of the ply helix angle.

E.   FLEXIBILITY

Woven structures comprised of conventional textile fibers are unique as sheet materials because of their unusually high flexibility. This flexibility manifests itself in several planes of bending at the same time. A woven structure is characteristically different from a sheet of paper in that it can bend on a three-dimensional surface in a multiplicity of ways. Its ability to shift from two dimensions to three dimensions is achieved by a number of mechanisms:  by thread shear, local crimp interchange, yarn buckling at the bend, yarn flattening, yarn compaction, fiber slippage, fiber rotation, fiber extension, and fiber bending (52).

The simple act of weaving requires the bending of one yarn around a cross yarn of approximately the same radius. If the yarns were monofilament in nature, this bending, were it elastic, would result in an outside strain of 50%. In a multifilament yarn with no fiber slippage, a similar high strain would occur, were no twists available to reduce geometrically the strain level in the outmost fiber. It has been shown that the level of twist occurring in a yarn bent to a radius of curvature equal to twice its own radius is affected directly by the local helix angle of fibers within the yarn (31). The act of bending modifies the local helix angle significantly so that the final strain due to bending a yarn around its original centroid will differ at the inside of the bend vs. the outside of the bend. However, the influence of fiber twist on the level of fiber strain in the bending of one yarn over the other is not sufficient to explain the ability of many commercial fibers which have elongations at rupture of less than 5%, performing satisfactorily in fabric structures which are subjected to bending either during processing or during use. The conclusion has been reached (29, 53) that fiber slippage within the yarns structure prevents build up of high strain and high stress level within the textile structure during bending. If complete freedom of movement of fibers within a twisted yarn exists then the bending resistance or bending moment of a yarn can be calculated from the product of curvature and bending rigidity of the individual fibers, determining their appropriate moment components in terms of geometric position and configuration within the yarn structure. These moment components are then integrated to provide a measure of the total resistance of the bent yarn.

The ratio of stiffness of yarns with complete freedom of fiber slippage vs. those with no freedom of fiber slippage is usually of the order of the number of the fibers present (for a given size yarn, packing factor, and density). If the fiber is not free to slip one over the other, the yarn would appear to be exceedingly stiff as contrasted to the free slippage case, the ratio of stiffness being equal to the number of fibers present in the system. It is critical that freedom of motion is permitted within the twisted yarn structure to acquire the flexibility desired in the final fabric. As one increases the twist in the yarn it may be expected that the freedom of fiber slippage is somewhat reduced. On the other hand, the increased helix angles involved will serve, from a geometric point of view, to reduce the bending rigidity of the system. For conventional fibers with conventional twist, it does not appear that the restriction on fiber freedom is significantly increased with twist and most

observations on twisted structure show less rigidity at a higher twist level. This is true for extensional rigidity as well as for bending rigidity. Clearly a suitable parachute material must have complete flexibility for the purpose of packaging and for manipulation of the fabric structure during chute deployment.

The term 'balanced yarn' implies that the torque developed during the twisting operation has been effectively cancelled by the reverse twist of the ply structure. The extent of balance of twist is often determined microscopically, by comparing the direction of the outside fiber with the direction of the axis of the ply. If the two coincide, the ply yarn structure is termed 'balanced'. Of course putting 10 turns per inch in the singles yarn, say in the S direction, followed by 10 turns per inch Z twist in the ply direction is not a balanced twisting operation. This follows from the fact there is considerable contraction both in singles yarn and in ply yarn during the twisting operation and the judgement of turns per inch must be based upon the same unit length (usually they are not, in talking about singles versus ply turns per inch). Furthermore the matter of torque balance cannot be treated merely on a geometric basis. It must be analyzed both from the pointview of geometry of the fibers within the singles and ply structure and also in terms of the stress history of those fibers. When fibers are twisted into a singles yarn the individual element are subjected both to torsion and to bending. In a staple yarn, that is, one in which the filament lengths are discontinuous, the geometric torsion of the fiber path is fixed by the structure of the yarn. On the other hand, the mechanical torsion of the individual fibers, twisting them around their own axes may be relaxed out, by stress relaxation, or by natural rotation of the ends of the staple fiber within the yarn structure. This rotation cannot be detected easily nor can the extent of torsional stress relaxation be observed.

Platt has pointed out (51) that the major effect determining apparent twist unbalance of a yarn is due to the components of bending moment in individual fibers. These components are vector quantities which vary in direction with the position of the fiber within the yarn structure. It becomes important to develop exact expressions for fiber positions, for fiber geometric torsion, for fiber curvature, and then knowing the viscoelastic behavior of the fiber, express the local component of structural torque due to each fiber in terms of the fiber position in the yarn or ply cross section. This component or element of torque can then be integrated across the yarn structure to give a value for the

resultant torque or twist unbalance. This analysis has been carried out successfully by Platt and provides a worthwhile analytical start for fabric designers who are attempting to use fine filament wires in lieu of textile fibers.

Ply twist and singles twist are not the final determining factors in the matter of strength utilization. Singles twist in the case of staple yarn has been introduced to develop lateral pressures and therefore frictional contacts between fibers. The need for this frictional contact through the element of twist, is lessened if some other form of lateral pressure is available, as for example, the lateral pressures on a warp yarn developed by the cross yarns or filling yarn system. Over a period of years it has been shown that optimum twist in staple yarn, from a strength standpoint, could be reduced when the yarn was woven into a fabric so as to give optimum cloth strength performance. Commercially this was important, in that it allowed reduced spinning cost consistant with high strength output.

In the matter of filament yarns, higher twists have been shown to reduce strength of the yarns and in general they will also reduce tensile strength values of the woven fabrics. But at one stage one can anticipate an interaction between the absolute value of the singles twist or ply twist and the spacing of the cross yarns. Clearly in bending of a yarn as has been shown (31, 29) some fibers passing along the inside of the bend have to traverse a much shorter path than those fibers which have to pass over the outside of a bend. Pickup (39) has shown that if the singles yarn in a ply always holds the same position relative to the bending of a yarn in a fabric, the structural efficiency of the system will be significantly reduced. In other words, if some singles always lie on the inside of the yarn bend while others always lie on the outside, the strain and hence stress distribution on the ply yarn will be inequitable and a resulting low efficiency will be observed. Strength efficiency at a so-called pick-twist ratio of 2 was shown to be reduced by as much as 20%. This is an important factor to be considered in the design of parachute systems made of filamentous wire systems, for undoubtedly twisted structures will have to be used to achieve other desirable characteristics of a parachute fabric.

In addition to flexibility, or ease in bending in a parachute fabric structure one must have a high level of recovery from bending. In textile parlance this is called crease resistance. Obviously those fibers which are highly elastic in their stress strain behavior, that is to say, show very little secondary creep

at the temperature and humidity of use, will be highly crease resistant. They will show little permanent evidence of the bend to which the fabric has been subjected. Conversely those fibers which do not recover well at moderate strains, will show poor crease resistance in use. But recognizing the important contribution of fiber slippage to reduction of strain in individual fibers of the bent yarn it becomes important to note the role played by friction in the system. If friction in a yarn or in a fabric structure is high, either due to a high coefficient of friction, or to many points of contact, or to high lateral pressures (yarn twist caused or woven-fabric-structure caused) then it may be expected that frictional effects may be observable in measuring crease resistance or recovery from bending. As Daniels (53) has shown, the internal friction of the fabric structure must be taken into account in studying the recoverability behavior of individual fibers. One must determine the level of resistance to recovery imposed on the individual fibers due to their position in the fabric structure. In studying new fibers and measuring their recoverability, one must carry on such observations under the recovery restriction comparable to those which exist in the fabric. In other words, the recovery percentages cited above (35) must determined under a fixed recovery load rather than a zero recovery load. This modification in testing procedure, may serve to vary the ranking of various fibers with regard to their crease resistance contribution to fabric structure. Thus fiber properties, that is, inherent stress strain characteristics plus surface frictional characteristics plus geometric formation within the fabric structure all add together to establish the ability of a woven fabric to recover from a fixed bending strain. It has been shown in practical twisted structures that considerable fiber movement takes place internally within each bent yarn (31) and it follows quite logically that this movement must be reversed if good crease recovery is to be effected. In general where fiber properties are same, it may be concluded that crease resistance will be higher where bending resistance is lower. The greater strain energy stored in the system or the greater the bending work required to accomplish the sharp curvature, the more energy will be dissipated in the system and the less recovery will be observed from creasing. And so the following factors remain as important variables in achieving good crease resistance:

a. High recoverability of the fibers from strains incurred at the bend.

b.   Reduced friction within the yarn system.

c.   High helix angles to reduce the level of local strain
     at the bend.

The weave structure interacts to a significant degree in
bending behavior tests on textile fabrics.  In one case, it is
observed that the position of float on the surface of fabric
relative to bend is important.  If a long float runs longitudi-
nally into the bend, that is to say, if the long float being bent
is on the outside of the bend, then the bending rigidity of the
fabric is higher and recovery is generally lower.  If this float
runs parallel to the bend, the recovery characteristics are
slightly better.  If the float runs perpendicular to the bend
but lies on the inside of the bend, there is strong possibility
that the float will buckle rather than bend sharply at the inside
of fabric crease.  The recovery from this bending and torsional
buckling may or may not be good, depending upon the relative twist
tightness of the structure.  If the structure is highly twisted,
the buckling action and local kink which develops may not recover
easily and a permanent crease mark on surface of the fabric may
be observed when the fabric has been unbent.  This crease mark
may not necessarily be a projection from the plane of fabric,
but merely a systematic displacement buckling of the yarn laterally
within the fabric structure or fabric plane.

The angle between the bend line and the warp or filling is
also important in the crease resistance of the textile fabrics.
Recognize that if cloth is bent in one direction, the yarns run-
ning into the crease may be formed into a helix of the same
direction as their original twist helix or they may be formed
into an opposite direction helix.  If the helix directions coincide
there will be a tendency to tighten up the fabric or yarn struc-
ture and as a result incur higher bending resistance for the system.
If, on the other hand, the yarn is untwisted locally at bend the
rigidity of the yarn will be less at that point and the recovery
will be generally better.  This has been observed by measuring
the crease resistance of the given fabric and plotting recovery
in terms of a polar diagram (54, 55).  It is likewise possible to
measure bending rigidity of the yarn in a given plane and then
calculate the components of bending rigidity as a result of bending
that yarn in other planes, in other words, anticipating by the
analysis the bending rigidity of woven fabrics in different angles
of bend as a result of bending rigidity tests on singles yarn.

Finally it may be pointed out that the bending recovery of yarns may be effected in great extent by the compactness of yarn structure at the position of bend. One observes from textile experience on woolen yarn vs. worsted spun yarn, that the woolen yarn and woolen fabrics are much easier to bend, and recover much more readily from creasing whereas the worsted spun yarn not necessarily of wool fibers easily crease and likewise show poor recovery from creasing. This type of geometric manipulation is undoubtedly a requirement for the parachute designer interested in working with fine wire filaments. The unfortunate fact about meeting the requirements for fabric flexibility in accordance with the variables discussed above, is that many of the structural design steps which one take to increase flexibility tend to modify unfavorably other desirable characteristics for a parachute material. In particular, any attempt to reduce the packing factor of fibers within a yarn that is to say increase the relative air space within the yarn, will result in an increase in bulk of the fabric system and therefore of the total parachute. Likewise if twist is increased, the yarn bundle retains a round shape resulting in a higher bulk or thickness value. In addition, changes which increase the flexibility and extensibility of the fabric will result in an opening of the structure during the stress application of the parachute uses, with the resultant increase in porosity. Consider now the factor which influences compactness and bulk of the parachute fabric.

## F.  FABRIC BULK

The total package volume for a folded parachute is of course dependant upon the fabric bulk, the bulk of the hardware components, the bulk of the seams and the ability of the fabric to bend to sharp curvature along the line of fold. The question of hardware is beyond of the scope of this discussion. The question of flexibility and crease resistance has been discussed in the above section. It remains to consider the implication of fabric bulk or thickness and of seam structure, seam bulk, and seam efficiency. First we consider the bulk of fabric itself. Obviously, the thicker the yarn, the thicker will be the fabric, all other factors being kept constant. However in a woven structure one should recall that the effective thickness of the fabric is determined by the vertical spacing between the top of the face crown and the bottom-most portion of the back crown. If the fabric is woven symmetrically about the center plane, the same yarn system will form the set of crowns which project on both face and back of the

fabric. This structure is demonstrated in geometric studies of the fabric porosity (18). It is possible for both yarn crowns to project to the same level at the face and the back of fabric. Usually, this combination provides for minimum thickness or the maximum compactness in the woven structure. If the wave height of one set of yarns plus the diameter of that set, exceeds the sum of wave height and diameter of the second set, the larger sum will determine the thickness of the fabric (34, 18) and obviously in such a case the over all vertical crimp of the projecting set of yarns will be larger than in the non-projecting set of yarns. If the crimp in warp and filling is brought into balance, and the projecting yarns are level, the fabric will achieve both the minimum thickness and minimum porosity.

Another factor determining the thickness of the fabric is the vertical diameter of yarn. As has pointed out above, an increase in twist will increase roundness of yarn and therefore, for a given linear density, an increase in twist will increase the vertical diameter of the yarn and likewise increase the fabric thickness. Lower twist will allow the yarn to flatten considerably, thus reducing fabric thickness. In addition, high pressure treatment as in calendaring will further flatten the yarn structure and cause more effective bending and meshing of the cross yarn systems so as reduce fabric thickness. The inter-meshing of the fibers at the point of contact between warp and filling yarns is also considered important from the standpoint of the fabric thickness or compactness. If the warp fiber in contact with the filling fibers have the same direction there will be tendency towards merging or meshing of the yarn systems with a resultant reduction in thickness. This factor however is not considered to be an important one, because the most instances the helix angles of twisted yarns are sufficiently below 45° as to preclude effective nesting or merging of the two yarn systems. In those cases where the twist has been increased so that larger helix angle formed at the inside of the yarn bend is of the order of 45°, then the fibers do tend to nest. But penetration with such helix angles is reduced since the yarn twist corresponding to those helix angles provides for a rounder firmer yarn structure with larger vertical diameter, contributing directly to increase fabric thickness.

Clearly any attempt to bulk or crimp the individual filaments of the yarn for the purpose of increasing flexibility, extensibility or crease resistance, will result in a bulkier yarn with the greater thickness per unit linear density. All in all, one must conclude that the major structural effects which determine

fabric thickness are: a) the relative crimp distribution between warp and filling yarns and b) the twist of the individual yarns which determines yarn compactness and roundness. The factors such as nesting appear to be negligible in determining fabric thickness. The comments made about crimp have implied fabric symmetry about the center weave plane. If weave symmetry is not present, it may be expected that one set of yarn will project on the face side of the fabric and the other set of yarns project on the back side of fabric. This occurence observed in all unbalanced weaves, that is to say weaves of a satin nature or unbalanced twills etc. Here one observes the presence of long floats of one yarn system on the face of the fabric. Each of these floats tends to bulge or balloon in its middle, rising high above the center plane of fabric. The tucking stitch at the end of each float dives down very briefly into the fabric structure and then rises again. The wave height of center of the float may be several times that of the wave height of single diving tie-in. The same is true in the reverse, on the back side of fabric with the other set of yarns providing the major float. Thus one can effect a fabric thickness somewhat in excess of three times the yarn thickness whereas in the case of maximum compactness one has a fabric thickness equal to twice the average yarn diameter.

Cloth thickness will of course be a predominant factor in determining the thickness of seams or joints between panels of fabric forming the parachute. The ability of the fabric to bend and fold sharply at the seam will also influence seam thickness and bulk. Finally, the tightness of the stitch itself, together with the mechanical properties of the sewing thread will add to seam compactness. It should be clear that if the fabric is layered twice or four times at a seam and stitched firmly, the stiffness will go up by a factor far in excess of the doubling or quadrupling thickness. This is obvious when one stitches together two or three relatively flexible webbing structures in the forming conventional parachute harnesses. But seam structures afford a much greater problem than that of bulk alone. The matter of seam strength and the seam efficiency are critical in the utilization of high temperature fibers in conventional fabrics for parachute application.

## G.    SEAMS

Seam failures at a tensile load well below the strength of the fabric it joins can be attributed to four primary causes:

1. Weakness of original sewing thread or damage to the thread incurred during sewing.

2. Damage to the fabric yarn during the stitching operation.

3. Efficiency of the seam structure in the uniformity transfering stress from one fabric to the other.

4. Yarn pull out, or seam slippage.

The theory of yarn and cord strength has been developed to the advanced stage and can be applied with some modification to sewing threads as they lie in the seam. In view of the extreme bending to which thread is subjected during sewing and later in the seam, the mechanics of bent yarn must be considered in conjunction with the principle of straight yarn mechanics, if a complete theory of sewing thread strength is to be developed. But, by utilization of high strength thread, cords or strands and a variety of lock stitches, it becomes possible to eliminate thread breakage as a source of seam tensile rupture. One may then consider the remaining mechanisms of yarn damage and stress transfer efficiency without complication of thread breakage.

The subject of fabric damage incurred during sewing has received only scattered attention in the textile literature. Dorkin et al. (50) does much to elucidate the mechanism governing the injury suffered by yarn lying along and across the seam during the sewing operation. It is considered that the major part of sewing damage to fabrics occurs through over extension of yarn by the needle as it penetrates the fabric. If the needle is dull or its taper so great that segments of yarn are carried down into the throat plate, failure of yarn may occur as a result of pinching against the side of the throat plate hole. In general yarn failure occurs as a result of local extension to rupture as the needle separates the yarn in penetrating the fabric or splits the individual yarn. Yarn extension which occurs during sewing can of course be made smaller if the needle radius is reduced. A smaller needle size is possible so long as the desired sewing cord can negotiate the needle eyes. In some instances, reduction in needle size, together with reduction in thread size may result in an increased seam strength. In addition, if the ultimate elongation of various fibers used in the fabric is increased at rates of extension comparable to that found in the high speed sewing machine, it may be expected that yarn rupture due to sewing may be reduced.

Dorkin shows that the ratio of clamp length to the needle size is critical factor in determining the degree of yarn rupture which will occur during sewing -- the greater the ratio, the less the damage. For the fixed needle sizes this ratio will be proportioned to the effective clamping length. The latter quantity is dependant on a) yarn twist, b) inter fiber and yarn friction, c) fabric tightness, d) machine clamping. Higher twist reduces the effect of clamping length. If one considers the case of yarn clamp between two fixed jaws and pierced by a sharp needle, the effective clamping length can be shown to be a function of the original twist of yarn, the separation of fixed jaws corresponding to the distance over which local increases in twist may be distributed, the needle diameter, the degree of fiber packing, the lubricity of the fibers, and stress strain properties of the fibers. In practice of course, the individual yarn which lies in fabric is not held between two fixed jaws but between a series of pseudo clamps made up of pairs of transverse yarns. Each of these pseudo clamps contributes an increment of frictional resistance to rotation and movement of the yarn and therefore to twisted redistribution occasioned by needle puncture.

In the immediate neighborhood of the needle puncture, the yarns running along the seam will also be distorted to allow room for needle passage. Breakage of such yarn during sewing is common but damage of this type is limited to the few yarns which lie along the seam path. Local distortion of these longitudinal yarns has an indirect effect on breakage of the perpendicular yarn since the longitudinal stresses which accompany such distortion increase the magnitude of frictional pressures in the pseudo jaws and resistance to twist transfer from the point of puncture, out along the transverse yarn. If the longitudinal yarn along the seam is free to move away from the seam, the above mentioned stresses will be alleviated. Such slippage will depend upon fabric lubricity and fabric tightness as well as yarn stiffness and crimp distribution. Obviously if the fabric is more open and the yarn is more extensible and the lubricity greater, the chances of damaging the yarn in the fabric structure during sewing operation will be reduced.

Stress transfer at a seam implies the case where the fabric breaks along the seam line rather than the thread which comprises the seam. When a seamed fabric is subjected to a homogenous unidirectional stress perpendicular to its line of stitching the seam is considered to have the maximum efficiency if it can transfer a stress equal to the breaking strength of the fabric. Even

without yarn damage resulting from sewing, the optimum seam efficiency is rarely achieveo because of the inherent seam structure. The function of a sewing thread in a seam is similar to that of a rivet joining two steel plates. However there are major differences in the behavior of two joining media:    1) rivets transfer tensile stress from one joined plate to another but are themselves subjective to shear stresses, while a flexible sewing thread bends upon application of load to the seam and transfers the most of stress from one fabric to another by means of tension along the thread axis       2)    each rivet is isolated from its neighbor and therefore may be considered to act independently in the stress transfer, while the sewing thread is directly linked from stitch to stitch.

The tensile stress in the section of stitch which lies across the seam, that is in the direction of extermal loading, is carried over to that segment of the stitch which lies parallel to the seam.  Thus one notes a snubbing action as the thread first aligns itself with the direction of stress and then runs perpendicular to that direction as it snubs around yarn within the fabrics being joined.  When the load is applied to the stitch, it becomes to bend out of its original plane perpendicular to the direction of tensile load application.  In part, it aligns itself with the direction of tension and in part it aligns itself with the snub around the fabric segments caught within the stitches.  With this snubbing action, high stresses are applied to those yarn at the corner of stitch.  This high stress can be observed in the excess of non-uniform pulling of the yarns in a fabric as they approach perpendicular to the line of seaming.  The yarns   which lie at the end of each stitch gathering are stressed at higher level and those yarn that run into the center of each stitch. As the tension continues across the seam, the edge snubbed yarns will rupture first, with the failure moving successively inward towards the center of the stitch.  As in the case of the maximum stress utilization in twisted straight yarns, the shape of stress strain curve has an important influence on the strength efficiency in sewn seams.  It is clear that if the stress-strain curve has a flat portion near rupture and the total extension is large, then yarns which have been subjected to slightly higher stresses because of their position relative to the stitch ends, will be subjected to approximately the same loading as yarns which have moved directly into the center of stitch loop.  If the contrary is true, namely that the fabric yarns have a stiff stress strain curve in the region of rupture, with a small extension, tnen the strain inhomogeneity met at a stressed seam will result in early failure of the fibers at the stitch end, long before the fibers

or yarn moving directly into the center of stitch loop are stressed to high level. A low strength efficiency across the seam will be the result.

To reduce the inefficiencies in seam strength resulting from non-homogeneous strain application, the fabric designer may take several steps. He may reduce the amount of strain inhomogeneity by increasing the number of stitches short of damaging the yarns of the fabric, or he may modify the properties of the yarn so as to move higher on the stress strain curve of all fibers at the moment that the seam starts to fail. Another way of reducing strain inhomogeneity is to reduce the level of stress transfer at each stitch loop. This can be done as mentioned above by increasing the number of stitches per inch along the seam. Another way of course is to increase the number of stitch lines along the particular seam. Here for the same number of stitches per inch one may reduce the stress level per stitch by a factor of the number of stitch lines used in the seam structure. But with all these additional seam lines one may expect additional stiffness in the seam and also additional bulk which will be undesirable from the point of view of parachute application. This question has been met by the parachute manufacturer in using conventional materials. One should expect that the question will become more critical in the use of stiffer high temperature fiber.

An entirely different approach to the subject of seaming and joining sheet material to form a parachute structure is possible, and that is to use normal methods for joining materials or to eliminate entirely the need for joining. These approaches will be discussed in the following section on parachute fabrication.


H.  PARACHUTE FABRICATION

The basic requirements for parachute design frequently determines the mode of parachute fabrication. In some instances, the high but the controlled porosity of a ribbon parachute is required and this implies fabrication of a series of high strength ribbons and webbings to form the skeleton and in fact the body of the parachute. Where lower porosities are required, a solid chute is generally used and this involves cutting and sewing panels of fabrics which form the body of the chute. Reinforced webbings may be used structurally to reinforce the so-called solid chute but they have little influence on the over all porosity of the system. The porosity of the conventional solid chute is

determined to a major extent by the porosity of the fabric and the design of the chute relative to the vent opening. In the ribbon chute the porosity of fabric is generally considered to be negligible since the open spaces between the ribbons and reinforcing structural webbings are relatively large and offer virtually no resistance to passage of air.

In the case at hand we are considered a parachute of relatively little porosity. The likelihood is that a solid chute structure will be employed. If on the other hand the aerodynamic requirement of the high altitude, high temperature chute could be met by the use of webbing and ribbon structures, the difficulties in fabricating such a chute would be resolved to great extent. In other words, it would be relatively simple to make extremely thin bands of webbing and use a variety of method of joining webbings one to another. There is the possibility of using adhesives between fabric sections in such chute, reinforced by some sort of sewing. There is also possibility of weaving the high temperature fiber into webbings with excessively heavy selvages and excessively heavy pick insertion at predetermined intervals. This would then allow for joining of an unconventional nature between the webbing sections, either by an over stitch formation of the type of helical spring joint one finds in common stationery note books. A joint of this sort could be spanned by a high temperature organic coating which would melt or ablate out during the latter portion of the parachute's operational cycle, but would be present in the initial portion for a sufficient period to insure proper parachute deployment. If high temperature, high strength metal wire is used for the helical spring joints between reinforced edges of a relatively impermeable (perhaps coated) piece of webbing, such wire need not be coated uniformly across the joints, but should be available for operation without protective coating.

An entirely different procedure of fabricating a parachute is to avoid the requirement of cutting long sections of fabric into small panels and tnen rejoining them to form the three dimensional configuration of the parachute. This procedure in effect eliminates one step in the over all process from fiber production to parachute manufacture and that is the process of weaving or knitting <u>flat</u> goods. Once a high temperature or yarn (properly designed in the respect to twist according to the principles cited above) is available it should be possible to fabricate the exact form or at least close approximation to the final form of the parachute utilizing the relatively infinite length of the fibers and filaments which are available and laying them in the structure within a minimum amount of residual stress

and in a position closely corresponding to their final position in a conventional parachute structure.

In the field of knitted fabrics it has been found possible, sometime ago to modify the stitch formation and the number of stitches involved at any one line of loop insertion so as to develop a three dimensional curvature. Thus full fashioned hosiery suggests one approach to the formation of the parachute with the required three dimensional curvature but without the necessity of the conventional seaming or joining of panels of two dimensional material. The three dimensional nature of knitted structures is evidend in several developments of artificial artery made on knitting machines. Here one is able to form two cylind- rical tubes and then join them in a 'y' shaped section. In the knitting the possibilities are open for developing three dimen- sional curvatures for introducing reinforcing elements, for modifying the geometry of the total structure with relatively ease. Of course the knit material which is obtained is formed with a multiplicity of interlocking loops. The loop structure of such a material lends to its extensibility and lack of dimensional rigidity. This feature may be desirable to offset the likely high rigidity and low extensibility of the high temperature material selected for the parachute. But it suggests an added difficulty in maintaining the structural integrity of the para- chute with respect to the low porosity, particularly during the time of maximum stress during deployment. The question as to whether knitted structures can be useful in connection with a high temperature coating of the basic high temperature fiber must be answered by further study and experimentation in the actual program of high temperature parachute development.

Another approach which has considerable historical back- ground is that of weaving a shaped fabric. The Jacquard loom developed many years ago in France, has been used as commercial machine to modify the shape and design of woven fabric with an infinite variety of combinations. Recently the Raymond Deicer and Engineering Company presented a paper at the Textile Research Institute meeting in New York (March, 1959) in which A.R. Campman described the potentiality of modifying the basic Jacquard loom so as to permit the weaving of a three dimensional structure. This modification consists primarily of utilizing the Jacquard mechanism to control the gross profile of the structure which is being woven. At the same time the modification of take up of the individual warp yarn allows for the introduction of fullness or tightness in various portions of the material. The net result is the development of a wide variety of shapes which can be

trimmed and applied directly to forms as a basis for structural reinforcement of plastic items. Forms such as boxes and helmet cover boats, nose cones, radomes, etc., have been successfully engineered according to Campman. There is no restriction on the combinations possible with a system of this sort. In addition, wide looms are available for such experimental development and techniques have been developed by Campman which utilize a folding system of weaving (not unlike the double cloth weaving of pillow slips or diaper materials). Such folding techniques permit the integral multiplication of the effective diameter of the parachute which may be woven on such a system. In addition, by controlling the filling introduction at any one level band reinforcement can be introduced at time around the circumference of the chute. Likewise the Jacquard control permits introduction of warpwise reinforcement at any point. This reinforcement can be introduced in the form of heavy structural webbings suitable for direct mechanical attachment to the hardware comprising the link with the object to be slowed down.

Thus in a practical production method (which obviously require considerable engineering work prior to development of a particular parachute structure) one has an opportunity of building a three dimensional structure with the controlled porosity and then introducing into the structure an inter-woven reinforcement and elements of structural linkage between the main parachute body and the system to be retarded aerodynamically. There are limitations on the curvature which can be achieved with such systems. In addition one must recognize that the introduction and removal of the continuous warp yarn from the fabric by the Jacquard mechanism means that the exit of the yarn from the fabric must be clipped off. This short loose end runs at a very shallow angle into the 'apparent joint' of the material and thus does not reduce the cross direction strength of that 'apparent joint'. We use a term 'apparent joint' because the joining action is actually a continuous process with the filling yarns going completely across the joint but the warp yarns merging on the joint line at a very shallow angle and discontinuous at the specific intervals. Perhaps the term structural dislocation would be more appropriate for the three dimensional weaving system. But with the application of a coating to reduce the porosity of the final fabric it is doubtful that the loose ends mentioned will pose any problem of significance. The three dimensional weaving in an opinion of the writers poses a challenging approach to the problem of fabricating rigid, inextensible, and in some cases relatively brittle fibers into a complicated parachute structures with the maximum structural and operational efficiency.

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